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	Engineering and Design HYDROLOGIC ENGINEERING REQUIREMENTS FOR FLOOD DAMAGE REDUCTION STUDIES	
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US Army Corps
of Engineers

ENGINEERING AND DESIGN

Hydrologic Engineering Requirements for Flood Damage Reduction Studies

ENGINEER MANUAL

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

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31 January 1995

Engineering and Design
HYDROLOGIC ENGINEERING REQUIREMENTS FOR FLOOD DAMAGE REDUCTION STUDIES

1. Purpose. This manual presents basic principles and technical procedures for hydrologic engineering analysis of flood damage reduction measures.

2. Applicability. This manual applies to HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities (FOA) having civil works responsibilities.

3. General. Procedures described herein are considered appropriate and useable for hydrologic engineering analyses required for planning and design of flood damage reduction measures. Basic concepts and procedures for analyzing selected flood damage reduction measures are presented. Emphasis is placed on hydrologic engineering analyses required for economic evaluations and performance criteria associated with various measures. The manual overviews the planning problem, identifies requirements for properly sizing, locating, operating, and maintaining flood damage reduction measures. The without-project conditions and measure-specific requirements are defined. Appendices provide references to additional technical guidance and summarize computer program capabilities for meeting the plan evaluation needs.

FOR THE COMMANDER:

ROBERT L. VANANTWERP
Colonel, Corps of Engineers
Chief of Staff

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Chapter 1
Introduction

1-1. Purpose

a. Role. Hydrologic engineering plays a critical role in flood damage reduction planning. It provides technical information necessary to formulate alternative solutions to the flood damage problem and to evaluate those alternatives, thus permitting recommendation of a plan that best alleviates the problem while:

(1) Yielding maximum net economic benefit;

(2) Performing efficiently and effectively, even under extreme events; and

(3) Protecting the Nation's environment.

This manual provides guidance for fulfilling this role.

b. Scope. Chapter 1 describes the planning problem, the flood damage reduction measures that may be included as solutions, the criteria for identifying the recommended solution, and the policies and procedures to be followed in the systematic search for the recommended solution. Subsequent chapters identify requirements for properly sizing, locating, operating, and maintaining the measures. Common requirements are described in Chapter 2; Chapter 3 describes the without-project conditions; and measure-specific requirements are defined in Chapters 4-9. Finally, Chapter 10 describes how the measures may be combined and the formulation and evaluation requirements for such plans. Appendices provide references to additional technical guidance and a summary of computer programs that may be appropriate for meeting the information needs for plan evaluation.

1-2. Applicability

This manual applies to HQUSACE elements, major subordinate commands (MSC), districts, laboratories, and field operating activities (FOA) having civil works responsibilities.

1-3. References

Required and related publications are listed in Appendix A.

1-4. Flood Damage Reduction Planning Problem

a. Overview. The Federal objective in flood damage reduction planning is to identify a plan that will reduce the flood damage problem and "... contribute to national economic development consistent with protecting the Nation's environment, pursuant to national environmental statutes, applicable executive orders, and other Federal planning requirements (U.S. Water Resources Council (WRC) 1983 and ER 1105-2-100)." Typically, this is accomplished by formulating a set of likely solutions, evaluating each in terms of the national economic development and other standards, comparing the results, and identifying the recommended plan from among the set.

b. Basis for comparison. The measure of a flood damage reduction plan's contribution to national economic development (NED) is the net benefit of the plan. This is computed as the sum of location benefit, intensification benefit, and flood inundation-reduction benefit, less the total cost of implementing, operating, maintaining, repairing, replacing, and rehabilitating (OMRR&R) the plan. Location benefit is the increased net income of additional floodplain development due to a plan. Intensification benefit is the increased net income of existing floodplain activities. Inundation-reduction benefit is the plan-related reduction in physical economic damage, income loss, and emergency cost.

c. Plan components. A flood damage reduction plan includes one or more of the flood damage reduction measures listed in Table 1-1. The planning study determines which of these measures to include in the plan, where to locate the measures, what size to make the measures, and how to operate the measures. According to WRC guidelines, a study proceeds by formulating, evaluating, and comparing "various alternative plans ... in a systematic manner." That is, candidate combinations of measures, with various locations, sizes, and operating schemes, are proposed. Each alternative is evaluated with the criteria described previously. Of those formulated and evaluated, that alternative that reasonably yields the greatest NED contribution is referred to colloquially as the NED plan. Subsequent chapters in this manual provide guidance on selecting appropriate locations, sizes, and operation policies and describe how the inundation-reduction benefit due to each of the measures can be estimated.

Table 1-1
Flood Damage Reduction Measures[1]

Measures that reduce damage by reducing discharge	Measures that reduce damage by reducing stage	Measures that reduce damage by reducing existing damage susceptibility	Measures that reduce damage by reducing future damage susceptibility
Reservoir	Channel improvement	Levee or floodwall	Land-use and construction regulation
Diversion		Floodproofing	
Watershed management		Relocation	Acquisition
		Flood warning and preparedness planning	

[1] In general, not a detailed specification.

d. Standards. In addition to yielding maximum NED contribution, the flood damage reduction plan recommended for implementation must

(1) Protect the environment, consistent with the National Environmental Protection Act (NEPA) and other laws, orders, and requirements; and

(2) Be complete, efficient, effective, and acceptable (U.S. Water Resources Council 1983), consistent with regulations, orders, and other legal requirements. (EP 1165-2-1 summarizes these.)

These limitations are referred to herein as the environmental-protection standard and the performance standard, respectively. Plans must be formulated to satisfy both standards, and analyses must be carried out to confirm that they do. A plan that satisfies both is declared feasible.

e. Further guidance. Further guidance on formulating plans and evaluating their feasibility is presented in Chapter 2. Subsequent chapters address the requirements for individual measures.

1-5. Corps Procedure for Finding a Solution to the Planning Problem

The Corps's approach to solving the flood damage reduction problem is through a sequential process that involves planning, design, construction, and operation. Planning or feasibility studies are performed in two phases, reconnaissance and feasibility, and conclude with recommending a plan for design and implementation.

a. Reconnaissance. In the first phase, the reconnaissance phase, alternative plans are formulated and evaluated in a preliminary manner. The goal is to determine if at least one plan exists that has positive net benefit, is likely to satisfy the environmental-protection and performance standards, and is acceptable to local interests. In this phase, the goal is to perform detailed hydrologic engineering and flood damage analyses for the existing without-project condition if possible (USACE 1988a). If a solution can be identified, and if a local sponsor is willing to share the cost, the search for the recommended plan continues to the second phase, the feasibility phase.

b. Feasibility. In the feasibility phase, the set of feasible alternatives is refined and the search narrowed. The plans are nominated with specific locations and sizes of measures and operating policies as illustrated by Table 1-2. Detailed hydrologic and hydraulic studies for all conditions are completed as necessary "... to establish channel capacities, structure configurations, levels of protection, interior flood-control requirements, residual or induced flooding, etc." (ER 1110-2-1150). Then, the economic objective function is evaluated, and satisfaction of the performance and environmental standards tested. Feasible solutions are retained, inferior solutions are abandoned, and the cycle continues. The NED and locally preferred plans are identified from the final array. The process concludes with a recommended plan for design and implementation.

c. Design. In the design or preconstruction engineering and design (PED) stage, necessary design documents (DM) and plans and specifications (P&S) for

Table 1-2
Plan Formulation/Evaluation for Feasibility-Phase Studies

Nominate Range of Plans[1]	Iteratively Screen and Refine Plans[2]	Develop Final Array of Feasibility Plans[3]
Plan A	Plan A	Plan A
Plan B		
Plan C	Plan C	
Plan D		
Plan E	Plan E	Plan E[4]
.	.	
.	.	Plan G
.	.	
.	.	Plan I[5]
Plan M	Plan M	

[1] Wide range of potential plans each consisting of one or more measures.
[2] Continuous screening and refining of plans with increasing detail.
[3] Each plan must have positive net benefits and meet specified performance, environmental, and other standards.
[4] Plan that maximizes NED.
[5] Locally preferred plan.

implementation of the proposed plan are prepared. These further refine the solution to the point that construction can begin. Engineering during construction permits further refinement of the proposed plan and allows for design of those elements of the plan not initially implemented or constructed. Likewise, the engineering during operations stage permits fine-tuning of OMRR&R decisions.

1-6. Role of Hydrologic Engineering

Hydrologic engineering is an element of civil engineering that "... analyze[s] water and its systems as it moves above, on, through, and beneath the surface of the earth" (EP 1110-2-10). Consequently, hydrologic engineering has "... a major participatory role in defining the flood hazard, locating and sizing flood damage reduction projects, and determining and assuring the functional and operational integrity of the project" (EP 1110-2-10). Hydrologic engineering provides hydrologic and hydraulic information, other engineering information, key components of the economic and ecological information, and input to the social-suitability and community well-being information.

1-7. Hydrologic Engineering Study Design

a. Proper administration of public funds requires that hydrologic engineering studies be well planned so the analyses will provide the information required for proper decision making, be completed on time, and be within budget. To maximize the likelihood that this will be the case, one or more hydrologic engineering management plans (HEMP) will be developed for all flood damage reduction studies. EP 1110-2-9 provides guidance on HEMP preparation. A HEMP defines the hydrologic and hydraulic information required to evaluate the NED contribution and to ascertain satisfaction of the environmental-protection and performance standards. It also defines the methods to be used to provide the information, and identifies the institutions responsible for developing and/or employing the methods. From this detailed technical study plan, the firm time and cost estimates, which are included in the HEMP, can be developed.

b. An initial HEMP is prepared at the end of the reconnaissance phase; this defines procedures and estimates resources required for the feasibility phase. At the end of the feasibility phase, a HEMP is prepared to define procedures and estimate resources for the PED phase. At the beginning of the feasibility and PED phases, a HEMP also may be prepared to define in detail the technical analyses. The contents of a HEMP vary slightly depending on the study phase, but all contain the best estimate of the work to be performed, the methods for doing so, and the associated resources required.

Chapter 2
Common Hydrologic Engineering Requirements

2-1. Summary

This and subsequent chapters define hydrologic engineering requirements for formulating and evaluating economically efficient flood damage reduction plans that will satisfy performance and environmental-protection standards. Some measures that may be included in a plan have unique requirements for formulation and evaluation. Others have some common requirements. These common requirements are described in this chapter and are summarized in Table 2-1.

2-2. Study Setup and Layout

Technical information is required to support the tasks of problem definition, plan formulation, and plan evaluation. The specific information needed and commensurate level of detail are dependent on the nature of the problem, the potential solutions, and the sensitivity of the findings to the basic information. Actions performed to set up and lay out the study are preliminary to the detail analysis. They include: defining the study scope and detail, field data collection and presence, review of previous studies and reports, and assembly of needed maps and surveys. Although this process involves more information gathering than analysis, it helps scope the study, lends credibility to the subsequent analysis, and provides insights as to potential solutions.

Table 2-1
Summary of Common Requirements

Objective or Standard	Requirement	Method/Model	Reference
Economic objective	Develop discharge-frequency function and uncertainty	Frequency analysis or ungauged catchment methods	EM 1110-2-1417 EM 1110-2-1415 ER 1110-2-1450
	Develop stage-discharge function and uncertainty	Observation or fluvial & alluvial process models	EM 1110-2-1416 EM 1110-2-1601 EM 1110-2-1612 EM 1110-2-4000
	Develop stage-frequency function and uncertainty	Statistical + system accomplishment models	EM 1110-2-1415
Performance standard	Determine expected annual exceedance probability	Risk-based analysis procedures	
	Determine expected lifetime exceedance probability	Hydrologic risk binomial distribution	EM 1110-2-1415
	Determine operation for range of events and assumptions	Hydrologic/ hydraulic models	ER 1110-2-1405 ER 1110-2-401
	Determine capacity exceedance consequences	Depends on measures	
	Perform reliability evaluation	Risk-based analysis procedures	
Environmental-protection standard	Assess impact	May require runoff, fluvial, alluvial, statistical-process models	ER 200-2-2

2-3. Requirements for Evaluating the NED Contribution

a. Benefit evaluation standard.

(1) As noted in paragraph 1-4, the economic efficiency of a proposed flood damage reduction alternative is defined as

$$NB = (B_L + B_I + B_{IR}) - C \qquad (2\text{-}1)$$

in which NB = net benefit; B_L = location benefit; B_I = intensification benefit; B_{IR} = inundation-reduction benefit; and C = total cost of implementing, operating, maintaining, repairing, replacing, and rehabilitating the plan (the OMRR&R cost). The inundation-reduction benefit may be expressed as

$$B_{IR} = (D_{without} - D_{with}) \qquad (2\text{-}2)$$

in which $D_{without}$ = economic flood damage without the plan and D_{with} = economic flood damage if the plan is implemented.

(2) The random nature of flooding complicates determination of the inundation-reduction benefit. For example, a flood damage reduction plan that eliminates all inundation damage one year may be too small to eliminate all damage in an extremely wet year and much larger than required in an extremely dry year. WRC guidelines address this problem by calling for use of expected annual flood damage. Expected damage accounts for the risk of various magnitudes of flood damage each year, weighing the damage caused by each flood by the probability of occurrence. Combining Equations 2-1 and 2-2, and rewriting them in terms of expected values, yields

$$NB = B_L + B_I + (E[D_{without}] - E[D_{with}]) - C \qquad (2\text{-}3)$$

in which E [ ] denotes the expected value. For urban flood damages, this generally is computed on an annual basis because significant levels of flood damage are limited to annual recurrence. For agricultural flood damages, it may be computed as the expected damage per flood, as more than one damaging flood may occur in a given year. The NED plan then is the alternative plan that yields maximum net benefit, accounting for the full range of likely hydrologic conditions that might occur.

(3) The so-called "without-project" condition in Equation 2-3 represents existing and future system conditions in the absence of a plan, "... accounting for the effect of existing and authorized plans, laws, policies and the flood hazard on the probable course of development" (EP 1165-2-1). It is the base "... upon which alternative plans are formulated; from which all benefits are measured; against which all impacts are assessed ..." (EP 1165-2-1).

b. EAD computation. Chapter 7 of EM 1110-2-1415 describes alternative approaches to computing the expected value of annual damage (EAD). The most widely used approach in the Corps is the frequency technique, which is illustrated in Figure 2-1. To compute

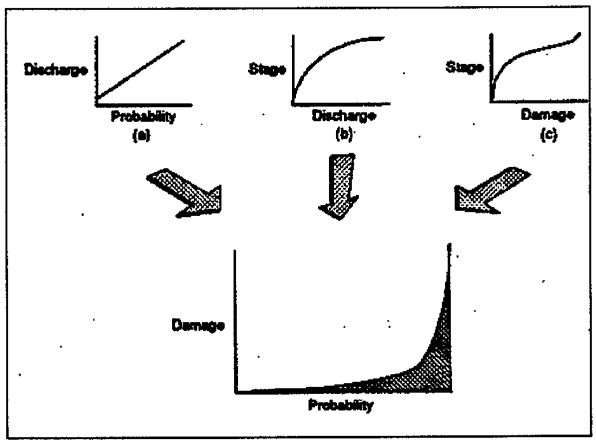

Figure 2-1. Derivation of damage frequency function from hydrologic, hydraulic, and economic information

EAD with this technique, the annual damage frequency function is derived and integrated. This damage frequency function commonly is derived from the annual maximum discharge frequency function (Figure 2-1*a*), transformed with a stage discharge (rating) function (Figure 2-1*b*), and a stage damage function (Figure 2-1*c*). This stage damage function may represent a single structure or it may be an aggregated function that represents many structures, their contents, and other damageable property. Dynamic catchment, channel, or economic conditions are accounted for by adjusting the appropriate functions and deriving and integrating the damage frequency function to compute EAD for the present and for each future year. The resulting EAD values can be

averaged over project life, with discounting if appropriate. The transforming, integrating, and discounting computations can be performed by the Hydrologic Engineering Center's (HEC) EAD program (USACE 1989a), which is described in Appendix B. The task of the hydrologic engineer is to define the discharge frequency function and rating function for various alternatives, including the without-plan case, for existing and future system conditions. Procedures and analytical tools for doing so are described in various Corps publications and are summarized in paragraph 2-3(*d-f*) for convenience.

c. Risk-based analyses.

(1) The procedure illustrated in Figure 2-1 ignores uncertainty in the functions. Uncertainty is due to measurement errors and the inherent variability of complex physical, social, and economic situations. Traditionally, the Corps has accounted for this uncertainty by employing factors of safety, such as levee freeboard. However, the state of the art of risk analysis has advanced sufficiently as of the early 1990s to permit explicit accounting for uncertainty. Consequently, Corps policy is that all flood damage reduction studies will adopt risk-based analysis. Figure 2-2 illustrates the analysis strategy.

(2) The risk-based analysis procedure seeks to quantify the uncertainty in the discharge frequency function, stage discharge function, and stage damage function and to incorporate this analysis of the economic efficiency of alternatives. This is accomplished with Monte Carlo simulation, a numerical-analysis tool that yields the traditional estimate of the expected damage reduced, accounting explicitly for the errors in defining the discharge frequency function, rating function, and stage damage function. In addition, the Monte Carlo simulation procedure provides an assessment of the project performance

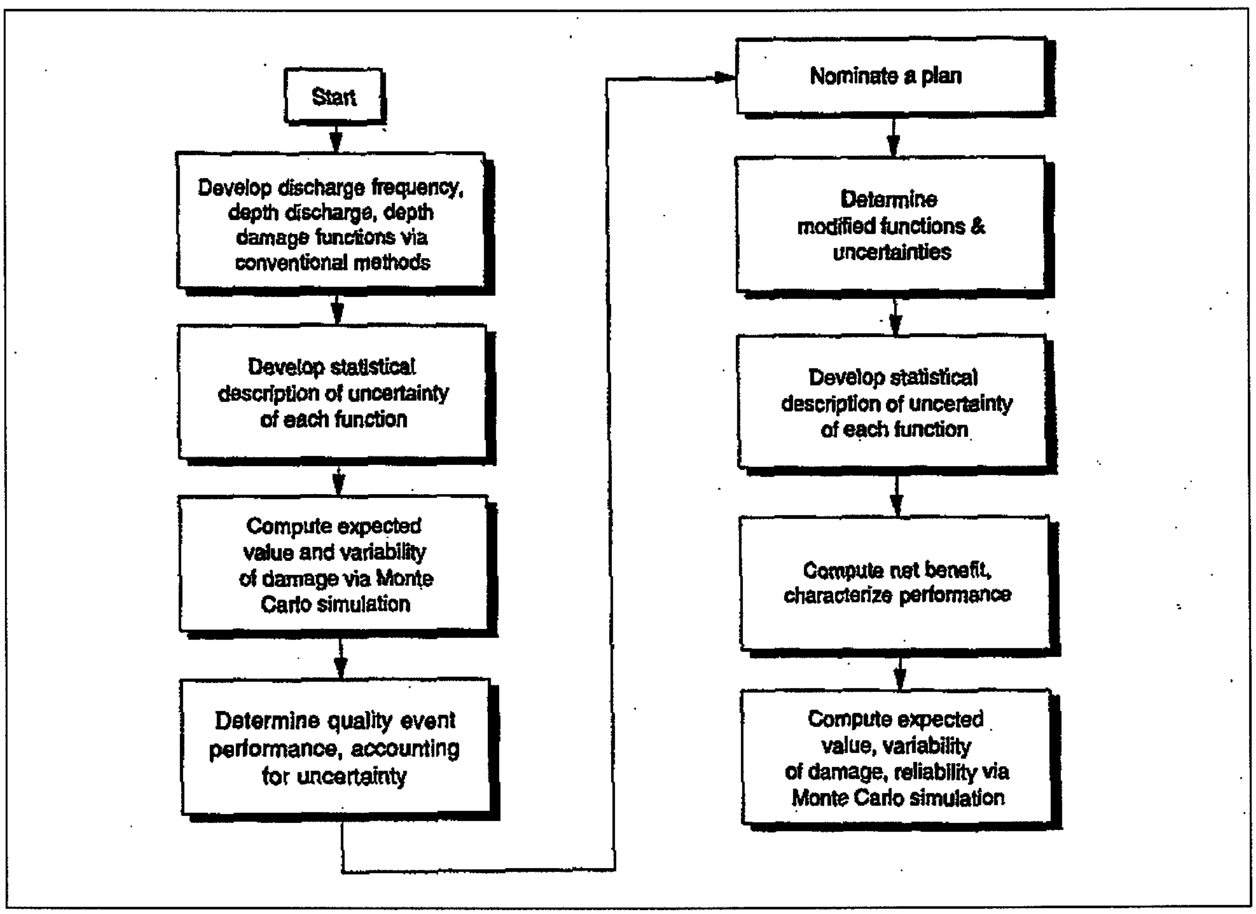

Figure 2-2. Risk-based analysis procedure

as described in paragraph 2-4. Performance indicators derived are the expected annual exceedance probability and reliability of a flood damage reduction plan. The expected annual exceedance probability is the chance of flooding in any given year. Respectively, this is an index of the frequency with which the plan performs as designed. For example, in analysis of a proposed levee sized to contain the 1 percent chance event, this procedure would estimate the probability that the levee would, in fact, contain the 1 percent chance and other events, should these occur.

d. Discharge frequency function definition.

(1) The manner in which the discharge frequency function is defined depends on the data available. For the existing, without-plan condition, if a sample of annual maximum discharge is available for the appropriate stream, the frequency function can be developed by fitting a statistical distribution with the sample. The procedures adopted by the Corps follow the guidelines proposed by the Water Resources Council (Interagency Advisory Committee 1982). These procedures are explained in detail in EM 1110-2-1415 and serve as the technical basis for the HEC-FFA computer program (USACE 1992a). That program is described in Appendix B.

(2) If a sample of annual discharge for existing condition is not available and for future and with-project conditions, the discharge frequency function must be developed with one of the procedures listed in Table 2-2. These procedures are described in detail in EM 1110-2-1417. For special cases, such as regulated flows, different methods are required and must normally be augmented with modeling studies.

(3) The uncertainty in the discharge frequency function varies depending on the physical characteristics of the stream, quality and nature of the available data, and other factors. With-project conditions uncertainty of the discharge frequency function may be less or greater than the without-project conditions. Future conditions functions are almost always less certain.

e. Stage discharge function definition. The stage discharge function, or rating curve, for the without-project, existing condition may be defined either by observations or with model studies. For cases that modify the function, the stage discharge function must be defined with model studies. With-project conditions uncertainty may be less (concrete channel) or greater (not maintained) than existing without-project conditions. Future conditions uncertainty will most likely be greater.

Table 2-2
Procedures for Estimating Annual Maximum Discharge Frequency Function Without Discharge Sample (adapted from USWRC 1981)

Method	Summary of Procedure
Transfer	Frequency function is derived form discharge sample at nearby stream. Quantiles are extrapolated or interpolated for the location of interest.
Regional estimation of quantiles or frequency-function parameters	Quantiles or frequency functions are derived from discharge samples at nearby gauged locations. Frequency function parameters are related to measurable catchment, channel, or climatic characteristics via regression analysis. The parameter-predictive equation is used for the location of interest.
Empirical equations	Peak discharge for specified probability event is computed from precipitation with a simple empirical equation. Typically, the probabilities of discharge and precipitation are assumed equal.
Hypothetical frequency events	Unique discharge hydrographs due to storms of specified probabilities and temporal and areal distributions are computed with a rainfall-runoff model. Results are calibrated to observed events or frequency relations at gauged locations so that probability of peak hydrograph equals storm probability.
Continuous simulation	Continuous record of discharge is computed from continuous record of precipitation with rainfall-runoff model, and annual discharge peaks are identified. Frequency function is fitted to series of annual hydrograph peaks, using statistical analysis procedures.

Alluvial streams involving mobile boundaries, ice, debris, and flow bulking from land surface erosion can significantly add to the uncertainty of the stage discharge function estimates. Publications of the World Meteorological Organization (WMO 1980, 1981) describe procedures for measuring stage and discharge to establish empirically the stage discharge function for existing condition. In most cases, the Corps will rely on stage discharge relationships provided by the U.S. Geological Survey (USGS) for gauged sites or, in rare cases, will call on the USGS to establish relationships if these are deemed necessary but are not readily available.

(1) Gradually varied, steady-flow, rigid-boundary conditions. EM 1110-2-1416 describes use of physical and numerical models to establish stage discharge functions for existing, future, without-project, or with-project conditions. Commonly, a numerical model of gradually varied, steady-flow (GVSF), rigid-boundary in an open channel is used. Solution of the GVSF equations yields an estimate of stage at locations along a stream reach for a specified steady flow rate. To solve the equations, the channel geometry and hydraulic loss model parameters for the condition of interest must be defined. The geometry may be measured and parameters estimated for the existing channel condition or defined as part of the proposal for a flood-damage-reduction plan. One commonly used GVSF model, program HEC-2 (USACE 1982a), is described in Appendix B.

(2) Erosion and deposition.

(a) Channel bed, channel bank, and land surface erosion and deposition complicate evaluation of stage discharge function. Mobilization of bed and bank materials in alluvial channels alters the channel shape. If that happens, stage at a channel cross section is not a unique, time-invariant function of discharge, channel geometry, and energy losses. Instead, the stage depends on material properties and the time history of discharge, and a movable-boundary hydraulics model is required to define the relationship for EAD computation. Two such models, HEC-6 (USACE 1993a) and TABS-2 (Thomas and McAnally 1985), are described in Appendix B.

(b) Mobilization and subsequent deposition of the sediment may cause other complications if not anticipated. For example, construction of a reservoir will alter a stream's natural gradient, but the flow and sediment load moving in the channel upstream of the reservoir are not changed. As the stream reaches the reservoir, velocity decreases significantly. The response of the stream is to deposit the bed load and decrease the gradient immediately upstream of the reservoir. This effect moves upstream as more sediment is deposited. This can induce flood damages upstream of the reservoir. Downstream, the effect is to scour the channel and erode the banks due to the relatively clear releases of the reservoir. Continuous downstream migration of the instability problem is likely over time.

(c) Similarly, a channel straightening can alter the natural alluvial processes. Straightening increases the energy gradient while other conditions remain unchanged. This change can lead to increased erosion upstream of the realignment and increased deposition downstream. After some time, erosion of the channel banks and bed may occur.

(d) Likewise, land-surface erosion increases the sediment load on the stream resulting in bulking of the flows. Also, if significant watershed construction accompanied by removal of vegetation occurs, the sediment runoff will increase during the construction period. Unless proper precautions are taken for these conditions, this sediment may move into adjacent channels, where it will be deposited. This, in turn, reduces the channel cross-section area, increases the stage for a given discharge, and induces damage.

(e) EM 1110-2-4000 provides guidance on analysis of erosion and deposition impacts. It identifies locations at which sedimentation problems are likely to occur and suggests design or maintenance solutions to those problems.

(3) Ice impacts. Ice accumulations alter adversely accomplishments of flood damage reduction measures by restricting the flow in channels and conduits and by increasing pressure or forces on the measures. In cold regions, ice formation buildup and breakup must be anticipated, the impact must be evaluated, and project features must be adjusted to ensure proper performance. With some measures, such as channel-lining improvements, this translates to an increase in project dimensions so the measures can withstand impacts of floating ice. Likewise, if ice is likely to form on a reservoir surface, the dam design must be altered to withstand the increased overturning moment due to the added force on the dam. EM 1110-2-1612 and the Cold Regions Research Engineering Laboratory can provide guidance.

(4) Debris impacts. The effect of debris is similar to that of ice; it can significantly reduce channel conveyance

and constrict flows at obstacles. Examples are more volume associated with runoff, constrictions at bridges, and accumulation of urban trash and waste in channels. If debris is mobilized and subsequently redeposited, it may adversely affect performance of pumps, gates, and other plan features. Proper maintenance measures should be included as a component of any plan to avoid these problems.

f. Stage-frequency definition. If flood inundation results from a flooding river, storm surges along a lake or ocean, wind-driven waves (runup), a filling reservoir, or combinations of these events, a stage-frequency function is more appropriate for derivation of the damage-frequency function. EM 1110-2-1415 describes statistical-analysis procedures for fitting a frequency function with observations for a current, existing condition. The procedures are similar to those used for fitting a frequency function with a discharge sample. For future condition and other cases, the function must be defined with model studies. The model used depends on the condition to be analyzed. For example, if reservoir operation changes are proposed to reduce flood damage due to reservoir pool elevation rise, a reservoir-operation simulation model might be used to estimate the modified time series of lake levels. The stage-frequency function then could be fitted to this series with the methods of EM 1110-2-1415.

2-4. Requirements for Satisfying Performance Standard

Selecting the alternative that maximizes NED contribution provides for efficient investment of public funds, but it does not guarantee that a plan will perform as effectively as the public has a right to expect. Two plans may yield the same net benefit, but one may be less vulnerable and thus more desirable. For example, consider two hypothetical alternatives: a levee plan and a channel improvement plan, both sized and located to protect a floodplain from events less than the best-estimate of the 1 percent chance event. When a slightly larger event occurs, the levee will be overtopped and may be breached, causing significant losses. If this same event occurs with the channel plan, flow will be out-of-bank. However, the consequences of out-of-bank flow likely will be less significant than those associated with a levee breach. The channel project is less vulnerable. Performance indicators are used in determining the validity of the project and for comparing alternatives based on long-term project operational stability and public safety, and in determining potential significant damage locations. They include defining the flood risk for the project life, determining the expected annual exceedance probability, estimating the project reliability, describing the operation for a range of events and key assumptions, and defining the consequences of capacity exceedance events of each plan. Hydrologic engineering analyses are critical in the plan formulation phase to ensure that flood damage reduction plans satisfy the performance standard, functioning as anticipated. The performance indicators are described in more detail in subsequent paragraphs. EP 1110-2-8 may be used as a guide for explaining flood risk.

a. Expected annual exceedance probability. The expected annual exceedance probability is a key element of defining the performance of a given plan. It is the probability that the specified capacity or target stage will be exceeded in any given year. The value is determined from the risk-based analysis study that includes the uncertainties of the various functions. The target stage is normally that associated with the start of significant damage. For a levee or floodwall, the stage may be the stage where overtopping occurs. For a channel or nonstructural measures, the target stage may be that where flooding of the structures begins. Although variable for plans that modify the stage-damage function, the target stage should be consistent among plans that don't modify the stage-damage functions.

b. Expected lifetime exceedance probability. The probability that one or more flood events will occur within a specified time period, normally the project life, is a means of indicating performance. The calculations may be made directly using the binomial distribution as described in EM 1110-2-1415. Figure 2-3 graphically shows the relationships. The threat may be similar for all structures, such as behind a levee or floodwall, or

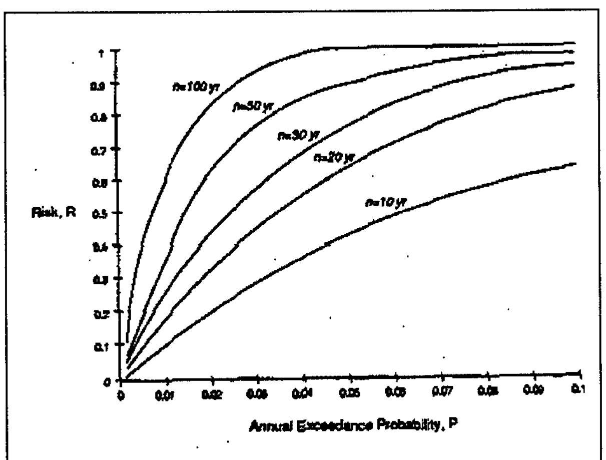

Figure 2-3. Probability of capacity exceedance during project life

variable depending on the elevation of individual structures, such as for a channel. For a channel example, a house located with the ground floor at the 1 percent chance flood level (the so-called 100-year flood level), the probability of one or more exceedances is approximately 0.40, or about one chance in 2.5 over a 50-year project life. If the house is located with the ground floor at the 0.5 percent chance level (the 200-year flood), the probability of one or more exceedances is 0.22. For a levee with an expected stage exceedance probability of 1 percent there is a 0.40 probability of one or more event exceedances during the 50-year project life for all the protected structures.

c. Operation for range of events and key assumptions.

(1) Each plan should be evaluated for performance against a range of events and key assumptions. Evaluation based solely on a specific design event is not a valid performance indicator by itself. For example, a pumping station must be configured to operate satisfactorily for a range of events, not simply designed for the 4 percent chance event. The analysis should be for a range of frequent and rare events including those that exceed the project capacity.

(2) Analysis of the sensitivity of the operation of the project to critical assumptions is required to assist in determining the stability of the project over its project life. An example is that there is a somewhat high likelihood of future encroachment of the natural storage associated with an interior system although it was not assumed as part of the plan assumptions. The sensitivity of the encroachment on the project performance should be evaluated. Similarly, the sensitivity of future development scenarios, erosion, debris, sediment, O&M, and other assumptions that are critical to having the project performed as planned and designed must be evaluated.

(3) The hydrologic engineering study is critical to development of the operation and maintenance plan as required by provisions of Federal Code 208.10, Title 33. It forms much of the basis for more detailed information included in the Operation and Maintenance Manual furnished local interests as provided for in the Federal Code. (ER 1110-2-1405 and ER 1110-2-401).

d. Consequences of capacity exceedance events. The project performance for one or more capacity exceedance events is required. Analyses to determine the extent, depth, and velocities of flooding and warning times for each event are conducted as part of the hydrologic engineering studies. Additional hydrologic engineering data to support definition of the population at risk, warning dissemination, and emergency response actions from the technical, social, and institutional perspectives for various times-of-the-day are also required. The hydrologic engineering studies to determine the consequences of the capacity exceedance events may vary significantly depending on the plan. Plans, such as levees and floodwalls, normally require the most detail because of the potential high loss potential. Flood-fighting efforts may be assumed as those necessary to preserve the integrity of the facility/system to pass the capacity exceedance event, no more-no less.

e. Event performance. This is the conditional probability associated with the chance of the project containing a specific event should it occur. The analysis is based on consideration of the uncertainties of the discharge-frequency and stage-discharge relationships. An example of this performance indicator is that the proposed levee would have a 75 percent chance of containing the 1 percent chance exceedance frequency event should it occur.

2-5. Requirements for Satisfying Environmental-Protection Standard

a. Policy. The policy of the Corps of Engineers is to develop, control, maintain, and conserve the Nation's water resources in accordance with the laws and policies established by Congress and the Administration, including those laws designed to protect the environment. The National Environmental Policy Act (NEPA) is the Nation's broadest environmental law. It requires that every Federal agency prepare an environmental impact statement (EIS) for proposed legislation or other major actions that would affect the environment significantly.

b. Corps procedure.

(1) For all Corps actions, except those categorically excluded from NEPA requirements, the Corps conducts an environmental assessment (EA) to determine if the action will have a significant impact on environmental quality. The EA presents the alternatives and defines the environmental impacts of each. In the event of a finding of no significant impact, no further action is necessary. Otherwise, an EIS will be prepared. The Corps normally prepares an EIS "... for feasibility reports for authorization and construction of major projects, for changes in projects which increase size substantially or incorporate additional

purposes, and for major changes in the operation and/or maintenance of completed projects (EP 1165-2-1)."

(2) NEPA requires that an EIS include the components shown in Table 2-3. Much of the scientific and engineering information required to develop these components is identical to or an expansion or extension of information otherwise required for economic and performance assessment. Hydrologic engineering studies are key providers of information for the EIS. For example, assessment of a proposed channel improvement may require erosion analysis. This same analysis may provide information required to assess the impact of the channel improvement on wildlife habitat along the channel banks. Coordination is required with environmental specialists to define such needs and to explore opportunities to expand the economic and performance analyses to provide the information. These resource requirements should be accounted for in the HEMP.

Table 2-3
Technical Components of EIS

1. Description of the alternatives considered, including at least the "no-action" alternative, the Corps' preferred alternative, and the "environmentally preferable" alternative;

2. Presentation of the environmental impacts of each alternative;

3. Explanation of why any alternatives were eliminated from further consideration;

4. Delineation of the affected environment;

5. Assessment of the environmental consequences of each alternative, including (a) direct effects; (b) foreseeable indirect effects; (c) cumulative effects from the incremental impact of the alternative plus other past, present, and foreseeable future actions; and (d) other effects, including unavoidable effects, irreversible or irretrievable commitments of resources, effect on urban quality, effect on historical and cultural quality; and

6. Actions that may be taken to mitigate adverse impacts, including (a) avoiding the impact by not implementing the plan; (b) minimizing the impact by limiting the plan; (c) rectifying the impact by repair, rehabilitation, or restoration; (d) reducing or eliminating the impact over time by preservation or maintenance; or (e) compensating by replacement or substitution of resources.

Chapter 3
Without-Project Conditions

3-1. Overview

This chapter presents hydrologic engineering requirements for performing existing and future without-project condition analyses as described by ER 1105-2-100. The results represent the base conditions for determining the economic value, performance, and environmental/social impacts of flood damage reduction measures and plans. Base conditions should be established in final detail as early in the process as possible to provide a stable basis of information and plan comparison. Table 3-1 presents a checklist that summarizes critical requirements for hydrologic engineering analysis for without-project conditions. This list and checklists in subsequent chapters are included as aids to ensure that nothing is left to chance. In most cases, the list items are described in more detail in the chapter. Some items, however, are listed just as a reminder to ensure that details will not be overlooked.

3-2. Layout

Hydrologic engineering plays an important part in the study setup and layout as described in paragraph 2-2. The layout for the existing without-project conditions is crucial to the overall study. Preliminary efforts define the study limits, review available information, and establish a field presence. These activities assist with development of the HEMP described in paragraph 1-7 and the initial definition of potential measures and plans to evaluate. Subbasins are delineated based on stream topology, gauge, sites, runoff characteristics, and locations of existing and potential measures. Assistance is provided to economists in estimating the maximum extent of flooding for structure inventories and defining damage reaches.

3-3. Technical Analyses

Hydrologic engineering investigations develop information that defines the flood characteristics used in the economic analysis and determination of the performance and environmental/social impacts of the existing system.

Table 3-1
Checklist for Without-Project Conditions

Hydrologic Engineering Study Components	✓	Issues
Layout		Review/assemble available information
		Conduct field reconnaissance for historic flood data and survey specification
		Establish local contacts
		Assist in establishing study limits, damage reaches
Economic Studies		Determine existing and future without-project conditions discharge-frequency and associated uncertainty
		Determine existing and future with-project conditions stage-discharge and associated uncertainty
Performance		Determine expected annual exceedance probability
		Determine expected lifetime exceedance probability
		Evaluate existing project operation/stability for range of events and key assumptions
		Describe consequences of capacity exceedances
		Determine event performance
		Formulate OMRR&R plan and prepare O&M manual to include existing system surveillance and flood fighting
Environmental and Social		Evaluate without-project riparian impacts
		Evaluate without-project social impacts

Information to be generated includes discharge-frequency, stage-discharge, flood inundation boundaries, warning times, and the variability of flooding (shallow or deep, swift or slow, debris and sediment laden, ice, etc.). The information is developed using previously described conventional studies. Uncertainties of the discharge, stage, and damage functions are determined for the existing without-project conditions. These relationships form the basis of estimating uncertainties for the future without-project and with-project conditions. Risk-based analyses are then performed to obtain economic and performance information. The nature of flooding and determination of the magnitude of major damage locations provide insights to the type and range of costs of potential flood damage reduction measures.

Chapter 4
Reservoirs

4-1. Overview

This chapter presents special requirements for formulating and evaluating flood damage reduction measures obtained by reservoirs. Reservoirs reduce damage by reducing discharge directly. Table 4-1 is a checklist that summarizes critical requirements for reservoirs.

4-2. Applicability

A reservoir is well-suited for damage reduction in the following cases:

a. Damageable property is spread over a large geographic area with several remote damage centers and relatively small local inflow areas between them.

b. A high degree of protection, with little residual damage, is desired.

Table 4-1
Checklist for Reservoirs

Hydrologic Engineering Study Components	✓	Issues
Layout		Consider alternative sites based on drainage area versus capacity considerations
		Delineate environmentally sensitive aquatic and riparian habitat
		Identify damage centers, delineate developed areas, define land uses for site selection
		Determine opportunities for system synergism due to location
Economics		Determine with-project modifications to downstream frequency function for existing and future conditions
		Quantify uncertainty in frequency function
		Formulate and evaluate range of outlet configurations for various capacities using risk-based analysis procedures
Performance		Determine expected annual exceedance probability
		Determine expected lifetime exceedance probability
		Describe operation for range of events and analyze sensitivity of critical assumptions
		Describe consequences of capacity exceedances
		Determine event performance
		Conduct dam-safety evaluation
		Formulate OMRR&R plan and prepare O&M manual to include surveillance and flood fighting
Design		Formulate/evaluate preliminary spillway/outlet configurations
		Conduct pool sedimentation analysis
		Evaluate all downstream hydrologic and hydraulic impacts
		Formulate preliminary operation plans
Environmental and Social		Evaluate with-project riparian habitat
		Evaluate aquatic and riparian habitat impact and identify enhancement opportunities
		Anticipate and identify incidental recreation opportunities

c. A variety of property, including infrastructure, structures, contents, and agricultural property, is to be protected.

d. Water impounded may be used for other purposes, including water supply, hydropower, and recreation.

e. Sufficient real estate is available for location of the reservoir at reasonable economic, environmental, and social costs.

f. The economic value of damageable property protected will justify the cost of constructing the reservoir.

4-3. Reservoir Operation Overview

a. Figure 4-1 illustrates a multiple-purpose reservoir. A reservoir reduces flood inundation damage by temporarily holding excess runoff then releasing that water downstream to the channel, either through the normal outlet system or over the emergency spillway for rare events, at a lesser rate over a longer period of time. This permits a reduction in peak flow rate, resulting in lower stage and less damage. The rate of release depends on the characteristics of the outlet works and spillway. Note that in the illustration, the outlet serves two purposes: It limits the release of water during a flood event, and it provides a method of emptying the reservoir flood control pool after the events.

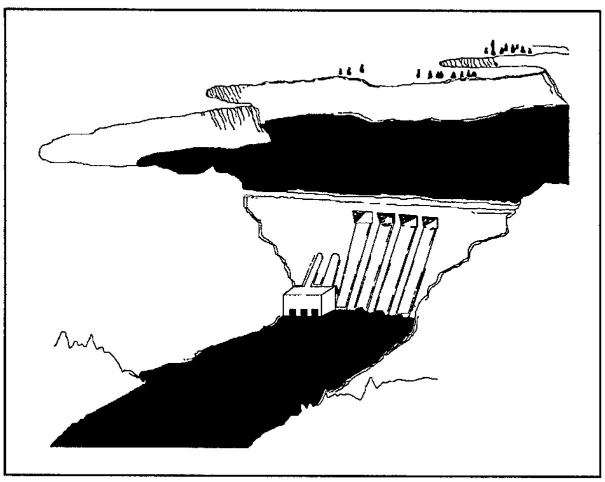

Figure 4-1. Multipurpose flood control reservoir

b. Detention storage systems are simpler flood storage systems normally implemented in urban settings as shown in Figure 4-2. They function in a manner similar to that of major reservoirs by modifying flood releases downstream of the project. The releases are typically uncontrolled such as shown in Figure 4-3. In this figure, the existing-condition, without-project peak discharge from a small catchment is 186 m^3/sec. This rate exceeds the maximum nondamaging discharge for the downstream reach, 113 m^3/sec, which is denoted "target flow" in the figure. To reduce the damage, storage is provided. The volume of water represented by the shaded area in the figure is held and released gradually at a rate that does not exceed the target. The total volume of the inflow and outflow hydrographs is the same, but the time distribution is altered by the storage.

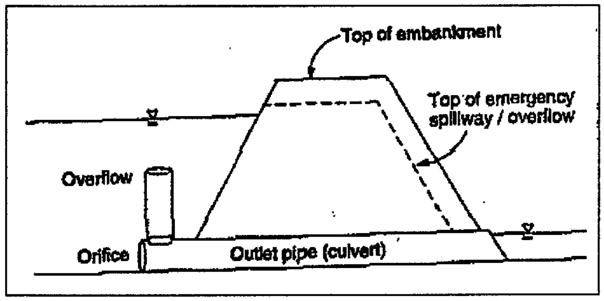

Figure 4-2. Simple detention storage facility

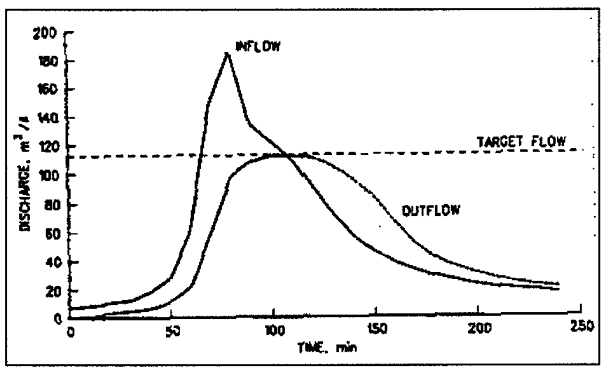

Figure 4-3. Impact of storage

4-4. Discharge-Reduction Assessment

a. The primary effect of storage is reduction of discharge, and this is modeled for individual runoff events with the routing models described in EM 1110-2-1417. Outflow from an impoundment that has horizontal water surface can be computed with the so-called level-pool routing model (also known as modified Puls routing model). A number of computer programs described in Appendix B include this reservoir routing model. The

reduction in discharge peak for individual events will translate, over the long term, into modification in the discharge-frequency function. This, in turn, yields a reduction in expected damage. The modified discharge-frequency function can be found by either:

(1) Evaluating reservoir operation with a long series of historical inflows and estimating regulated discharge probability from frequency of exceedance of magnitudes of the simulated reservoir outflow series, or

(2) Evaluating operation for a limited number of historical or hypothetical events. In this case, the probability of the unregulated inflow peak commonly is assigned to the peak of the corresponding computed outflow hydrograph. This is repeated for a range of runoff events to define adequately the modified discharge-frequency function. Hypothetical runoff events may be developed from rainfall-runoff analysis with rain depths of known probability, or from discharge duration-frequency analysis. In the first case, storms of specified probability are developed and the corresponding runoff hydrographs are computed with procedures described in EM 1110-2-1417. The runoff hydrographs are inflow to the reservoir. The peak outflows commonly are assigned probabilities equal to the corresponding storm probabilities. In the second case, a balanced inflow hydrograph is developed. This balanced hydrograph has volumes for specified durations consistent with established volume-duration-frequency relations. For example, a 0.10-probability balanced hydrograph is developed so the peak one-hour volume equals the volume with probability 0.10 found through statistical analysis of runoff volumes. Likewise, the hydrograph's 24-hour volume equals the volume with probability 0.10. With either of the hypothetical inflow events, reservoir operation is simulated and the outflow peak is assigned the same probability as the inflow hydrograph. This is repeated for a range of hypothetical rainfall events to define adequately the modified discharge-frequency function.

b. Figure 4-4 shows typical modifications to the discharge-frequency function due to a reservoir. In this figure, the solid line represents the inflow and the without-project outflow discharge-frequency function. (Note that the straight line shown here and in subsequent figures is a simplification for illustration. Discharge-frequency functions are not always straight lines when plotted on normal probability paper. See EM 1110-2-1415 for further explanation.) Q_1 represents a target flow; this may be the channel capacity downstream, the flow corresponding to the maximum stage before damage is incurred, or any other target selected for a particular floodplain. Ideally, a reservoir would be designed and operated to maintain releases less than or equal to this target. If the inflow peak is less than the target, the reservoir need not exercise any control. If the inflow peak exceeds the target, the reservoir should restrict outflow to the target rate. Consequently, the with-project frequency function, which is shown as a dashed line, is equal to the without-project frequency function for events of exceedance probability greater than P_1 (events with discharge less than Q_1). For inflow events of exceedance probability less than P_1 , release is limited to Q_1. However, regardless of the reservoir capacity, some extreme inflow events with peaks greater than Q_2 and probabilities less than P_2 will exceed the capability of the reservoir to limit the outflow to Q_1. The reservoir may reduce flow somewhat, but as the magnitude of the events increases (and the probability decreases), the regulated outflow peaks will approach the inflow peaks. The reservoir will have less and less impact. Finally, for an event with inflow peak equal to Q_3, the reservoir will have negligible impact, and the without-project and with-project frequency function will be identical.

4-5. Performance Considerations

The performance of a reservoir depends on its capacity, configuration, and location and on its operation rules.

a. Capacity, configuration, and location. Table 4-2 suggests steps for evaluating reservoir alternatives. Additional guidance is available in EM 1110-2-1602, in EM 1110-2-1603, from the Bureau of Reclamation (1977), and from ASCE/WEF (1992).

b. Operation rules.

(1) For a simple uncontrolled reservoir, discharge reduction, and hence damage reduction, depends on the hydraulic characteristics of the structure. The computations for these systems can be done with a specialized computer program, such as HEC-1. For a reservoir with gates and valves that can be controlled, the damage reduction depends also on operation rules. Operation rules specify how and when the gates and valves are to be opened. Typically, flood-control operation rules define the release to be made in the current time period as a function of one or more of the following: current storage in the reservoir, forecasted inflow to the reservoir, current and forecasted downstream flow, and current storage in and forecasted inflow to other reservoirs in a multiple reservoir system.

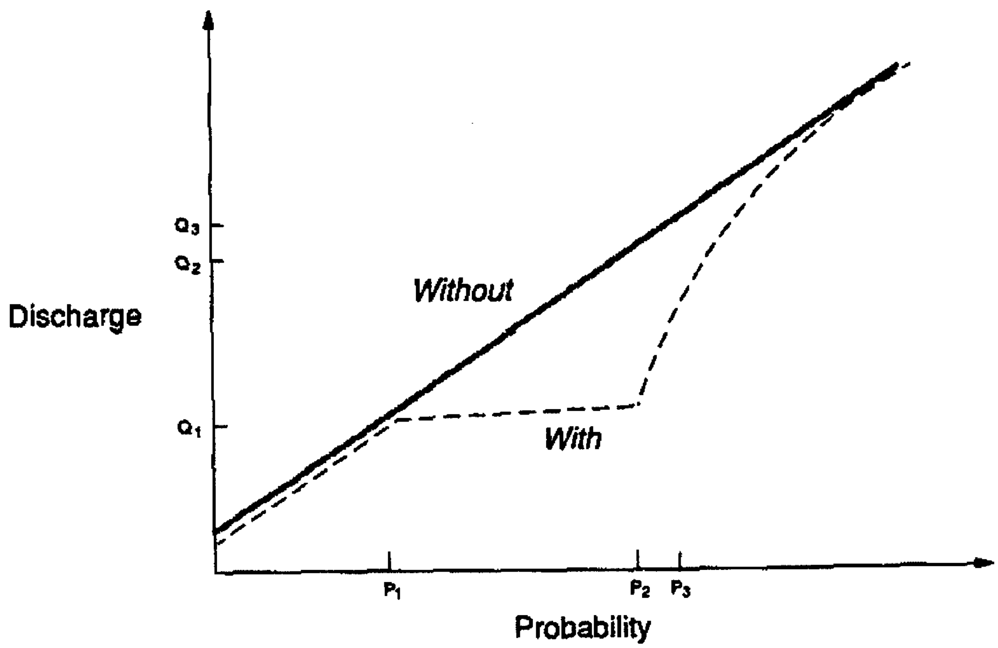

Figure 4-4. Discharge-frequency function modifications due to reservoir

Table 4-2
Steps in Evaluating Proposed Storage Alternatives

1. Define a set of without-project inflow hydrographs. These should cover the range of likely events, including frequent small events, infrequent large events, major historical events, etc.

2. Identify a "target" for reliability analysis. This may be the channel capacity downstream, the flow corresponding to the maximum stage before damage is incurred, or any other target appropriate for a particular floodplain.

3. Select a trial reservoir location, capacity, and outlet configuration. Develop the elevation-area-discharge functions required for reservoir routing for this alternative.

4. For each inflow hydrograph, in turn, compute the corresponding outflow hydrograph.

5. Compute the flood damage corresponding to the hydrograph peak.

6. Compare the outflow peak to the target to determine if the regulated flow or stage exceeds the target.

7. Repeat steps 3-5 for the range of inflow events. Determine the expected flood damage and the overall reliability of the alternative, defined as the frequency of meeting the target.

8. Repeat steps 2-6 for all reservoir alternatives.

9. Compare the economic efficiency and the reliability of the alternatives to select a recommended plan.

(2) Hydrologic-engineering studies formulate operation rules for controlled reservoirs as a component of any plan that includes such a reservoir. EM 1110-2-3600 presents guidance on operation rule definition. Computer program HEC-5 (USACE 1982b), which is described in Appendix B, is designed for simulation of flood-control reservoir operation. Publications from HEC describe how the program can be used to find operation rules.

(3) ER 1110-8-2 (FR) requires consideration of the effects of absence of personnel to regulate a reservoir, misoperation, and interruptions in communications during extreme events. For proper comparison of alternative plans, this cannot be simply an acknowledgement that these events may occur. A qualitative assessment must be made. For example, the hydrologic engineering analysis should define the discharge reduction possible for various events if the operator is making release decisions without knowledge of other than the reservoir pool elevation and the rate of pool rise.

c. Other considerations. To ensure proper performance of reservoirs for flood-damage reduction, the hydrologic engineer must consider also the following:

(1) Impact of debris/trash. A complete plan must include features that will minimize adverse impacts of outlet plugging due to debris.

(2) Safety features. A complete plan must include features to protect public safety at the reservoir site, particularly when the project is operating at capacity.

(3) Sedimentation. Chapter 5 of EM 1110-2-4000 provides a detailed description of sedimentation problems due to reservoirs, including those shown in Table 4-3. That EM also points out that "Eventually, all reservoirs will fill with sediment." The hydrologic engineer must conduct a sedimentation study to identify the problems and should include remedial features if necessary.

Table 4-3
Impact of Reservoir on Stream-System Morphology (from EM 1110-2-4000)

1. Rise in base level, and associated aggradation, of the main stem upstream from the dam due to the reservoir impoundment;

2. Fall in base level of the main stem downstream from the dam due to modified hydrographs;

3. Fall in base level of the main stem downstream from the dam due to degradation of the channel bed;

4. Changes in downstream channel capacity.

4-6. Dam Safety Evaluation

The discharge-reduction benefit of a reservoir is accompanied by the hazard of dam failure. Corps policy, as stated in ER 1110-8-2 (FR), is that "... a dam failure must not present a hazard to human life ..." Accordingly, any reservoir plan must be formulated to comply with this safety requirement, and the impact of catastrophic failure of any proposed reservoir plan must be evaluated to confirm that this performance constraint is satisfied.

a. Formulation to minimize catastrophic consequences when capacity is exceeded. ER 1110-8-2 (FR) identifies four design standards, depending on the type of dam and risk to life. Table 4-4 describes these. The hydrologic engineering study should determine the standard appropriate for plan formulation and ensure that the standard is used for all project features.

b. Failure evaluation. The impact of dam failure can be estimated with hydraulics models described in EM 1110-2-1416 or with the routing models of EM 1110-2-1417. Three aspects of dam failure must be considered by the hydrologic engineer: (1) formation of a breach, an opening in the dam as it fails; (2) flow of water through this breach; and (3) flow in the downstream channel. However, the operating characteristics of the reservoir change with time as the breach grows. For convenience in analysis, a breach commonly is assumed to be triangular, rectangular, or trapezoidal, and to enlarge at a linear rate. At each instant that the breach dimensions are known, the flow of water through the breach can be determined with principles of hydraulics. Subsequent movement of the outflow hydrograph through the downstream channel is modeled with one of the routing models.

4-7. Environmental Impacts

a. Construction of a reservoir can have significant environmental and social impacts, and information provided can be critical in evaluation of these impacts. Table 4-5 illustrates this; the list is by no means all-inclusive.

b. One particular serious environmental issue is preservation of wetlands. 40 CFR 230.41(a)(1) defines wetlands as "... those areas that are inundated or saturated

Table 4-4
Design Standards for Dam Safety

Standard	Application
1	Applies to dams located such that human life is at risk. In that case, the dam must be designed to pass safely a flood event caused by the probable maximum precipitation (PMP) occurring over the catchment upstream of the reservoir. PMP is a "... quantity of precipitation that is close to the physical upper limit for a given duration over a particular basin (WMO 1983)." Corps studies will use PMP amounts developed by the Hydrometeorological Section of the National Weather Service. Runoff from the PMP is computed using models and procedures described in EM 1110-2-1417 and EM 1110-2-1411.
2	Applies to dams "where relatively small differentials between headwater and tailwater elevations prevail during major floods." These structures must be able to pass safely major floods typical of the region, without incurring excessive damage downstream and without sustaining damage that would render the dam inoperable.
3	Applies to dams "where failure would not jeopardize human life nor create damage beyond the capabilities of the owner to recover." These structures should be planned so failure related to hydraulic capacity will result in no measurable increase in population at risk and in a negligible increase in property damage over nonfailure damage.
4	Applies to small recreational and agricultural water supply reservoirs. The design in this case is "... usually based on rainfall-runoff probability analysis and may represent events of fairly frequent occurrence." The decision likely will be based on economic considerations: Does the cost of a more reliable structure exceed the expected cost of repair or replacement?

Table 4-5
Hydrologic Engineering Information Required to Assess Environmental Impacts

Potential Impact	Hydrologic Engineering Information Required to Assess Impact
Loss of wildlife habitat due to ponding	Inundation due to and duration of ponding
Loss of vegetation in ponded area	Inundation due to and duration of ponding
Inundation of archeological sites	Extent of and depth of inundation
Increased in-stream temperature, increased turbidity, reduced dissolved oxygen downstream of reservoir	With-plan discharge-frequency, results of water quality simulation.
Improved recreational opportunities due to pond	Pond stage-frequency
Loss of downstream stream recreation due to reduced discharge	Discharge-frequency, stage-frequency

by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions (ASCE/WEF 1992)."

The hydrologic engineering study done in cooperation with environmental elements must identify any such areas to permit protection as required under Section 404 of the Federal Water Pollution Control Act.

Chapter 5
Diversions

5-1. Overview

This chapter presents special requirements for formulating and evaluating flood damage reduction by means of diversion measures. Diversions reduce damage by reducing discharge directly. Table 5-1 is a checklist that summarizes critical requirements for diversions.

5-2. Applicability

A diversion is well-suited for damage reduction in the following cases:

a. Damageable property is water from the system concentrated for bypass measures or spread over a large geographic area with relatively minor local inflows for diversions removing water from the system.

b. A high degree of protection, with little residual damage, is desired.

c. A variety of property, including infrastructure, structures, contents, and agricultural property, is to be protected.

d. Sufficient real estate is available for location of the diversion channel or tunnel at reasonable cost.

e. The value of damageable property protected will justify economically the cost of the diversion.

Table 5-1
Checklist for Diversion

Hydrologic Engineering Study Components	✓	Issues
Layout		Delineate environmentally sensitive aquatic and riparian habitat
		Identify damage centers, delineate developed areas, define land uses for site selection
		Determine right-of-way restriction
		Identify infrastructive/utility crossing conflicts
Economics		Determine with-project modifications to downstream frequency function for existing and future conditions
		Quantify uncertainty in frequency function
		Formulate and evaluate range of outlet configurations for various capacities using risk-based analysis procedures
Performance		Determine expected annual exceedance probability
		Determine expected lifetime exceedance probability
		Describe operation for range of events and analyze sensitivity of critical assumptions
		Describe consequences of capacity exceedances
		Determine event performance
		Formulate OMRR&R plan and prepare O&M manual to include surveillance and flood fighting
Design		Formulate/evaluate preliminary control structure configurations
		Conduct diversion channel sedimentation analysis
		Evaluate all downstream hydrologic and hydraulic impacts
		Formulate preliminary operation plans
Environmental and Social		Evaluate aquatic and riparian habitat impact and identify enhancement opportunities

5-3. Diversion Operation Overview

Figure 5-1 is a sketch of a diversion. This diversion includes a by-pass channel and a control structure that is a broad-crested side-overflow weir. Alternatively, this control structure might be a conduit through an embankment or a gated, operator-controlled weir, and a pipe or other conduit might be used instead of the open diversion channel. For the design illustrated, when the discharge rate in the main channel reaches a predetermined threshold, the stage at the overflow is sufficient to permit water to flow into the diversion channel. This, in turn, reduces discharge in the main channel, thus eliminating or reducing damage to the downstream property. Downstream of the protected area, the bypass and the main channel may join. A plan view of this is shown in Figure 5-2.

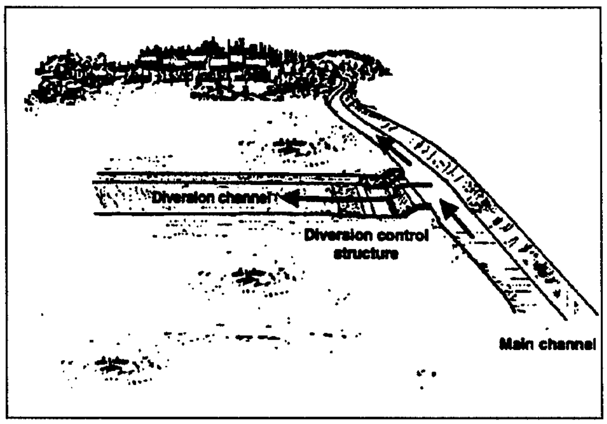

Figure 5-1. Major components of diversion

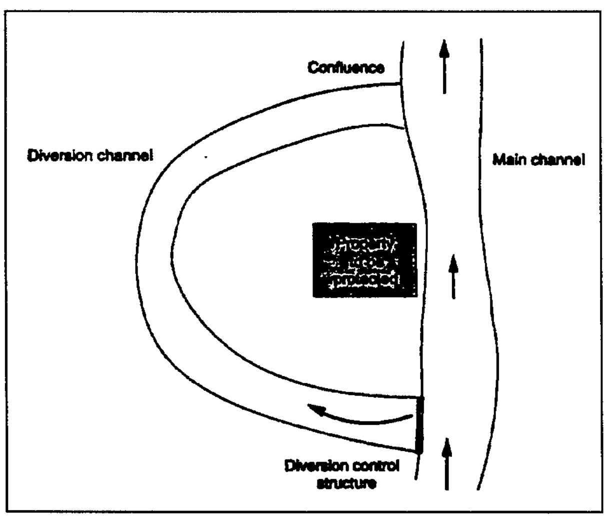

Figure 5-2. Plan view of diversion with downstream confluence

5-4. Discharge-Reduction Assessment

a. As a diversion alters discharge for individual flood events, it will eventually alter the discharge-frequency function. Figure 5-3 shows typical modifications due to a diversion. The solid line represents the without-project discharge frequency function at a location downstream of the diversion control structure. Q_1 represents a target flow at that point; as with a reservoir, this may be the channel capacity downstream, the flow corresponding to the maximum stage before damage is incurred, or any other target selected for a particular alternative. If the main-channel discharge is less than the target, no water need be diverted. When the main-channel discharge exceeds the target, the excess is diverted, limiting main-channel discharge to the target. Consequently, the with-project frequency function, which is shown as a dashed line, is equal to the without-project frequency function for events with exceedance probabilities greater than P_1 and discharges less than Q_1. The with-project function has flows equal to Q_1 when the main channel discharge exceeds this target. However, regardless of the design, some extreme event of probability P_2 will cause the bypass channel to reach its capacity. Then the diversion will no longer be capable of limiting main-channel flow to Q_1. Of course, the diversion may reduce main-channel discharge somewhat. However, as the magnitude of the events increases (and the probability decreases), the with-project main-channel discharge will approach the without-project discharge. Finally, for an event in which the without-project peak discharge equals Q_3, the diversion will have negligible impact, and the without-project and with-project frequency functions will be identical.

b. As with a reservoir, the impact of a diversion on the discharge-frequency function can be evaluated via period-of-record analysis or simulation of selected events. With the period-of-record analysis, the historical discharge time series is analyzed to estimate channel flow when the proposed diversion operates. The resulting modified main-channel discharge time series is analyzed with statistical procedures to define the frequency function. Otherwise, operation of the diversion with selected historical or hypothetical runoff hydrographs is simulated, and the resulting discharge peaks are assigned probabilities equal to the probabilities of the peaks without the diversion.

c. The behavior of a diversion can be modeled with the routing models described in EM 1110-2-1417. At the control structure, a hydraulic model estimates the distribution of discharge into the diversion channel and discharge

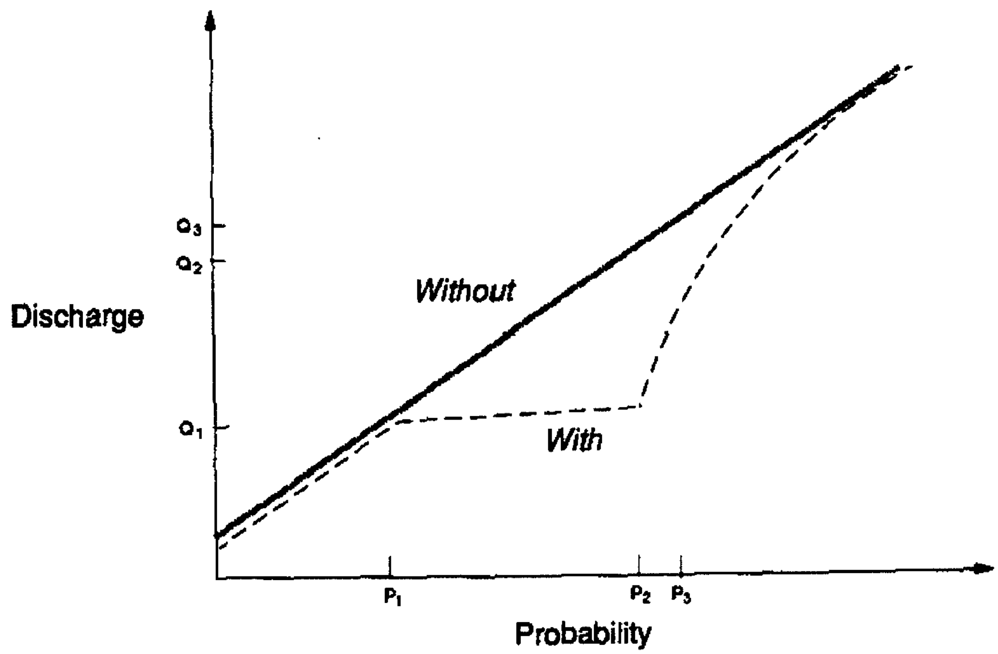

Figure 5-3. Discharge-frequency function modifications due to diversion

in the main channel. This model may be as simple as a diversion-channel flow versus main-channel flow rating curve derived with a one-dimensional gradually varied steady flow (GVSF) model or as complex as the two-dimensional models described in EM 1110-2-1416. Passage of flow in the diversion channel and in the main channel is modeled with a routing model, or, for more detailed analysis of the behavior, with a one-dimensional or gradually varied unsteady flow (GVUSF) model, or even a multi-dimensional flow model. EM 1110-2-1416 provides guidance in model selection.

5-5. Technical Considerations

a. The following potential problems must be considered to ensure proper performance of a diversion: channel stability, deposition, and safety during operation.

(1) Channel stability. A plan that includes a diversion must take care to ensure channel stability in both the diversion and main channels. Stability problems and solutions are described in EM 1110-2-1416 and EM 1110-2-1601, and are summarized in Chapter 4 of this manual.

(2) Deposition. EM 1110-2-4000 points out that "... deposition is a common problem at diversions." Consequently, a sedimentation analysis which estimates the magnitude of this problem and includes the plan remedial actions must be performed. This may include adjustments to the design to minimize deposition, or it might be limited to guaranteeing sufficient funds for continuous OMRR&R.

(3) Safety during operation. A diversion such as that shown in Figures 5-1 and 5-2 is an attractive nuisance. When the main-channel reaches the design level, and water is discharged into the bypass, the public will be attracted. Care must be taken to provide for public safety.

b. Further, under normal circumstances, a diversion channel is dry, so it is subject to unwise temporary or permanent use. If main-channel flows rise quickly, the diversion may begin to function with little advance notice, and the bypass channel will fill. Precautions should be taken to minimize damage within the channel or risk to life if the bypass channel is accessible to the public.

Chapter 6
Channel Modifications

6-1. Overview

This chapter describes the impact of channel modifications (sometimes called channel improvements) and hydrologic engineering requirements for planning these modifications to reduce flood damage. A checklist of the requirements is presented as Table 6-1.

6-2. Applicability

Channel modifications are effective flood-damage reduction measures in the following cases:

a. Damageable property is locally concentrated.

b. A high degree of protection, with little residual damage, is desired.

c. A variety of property, including infrastructure, structures, contents, and agricultural property, is to be protected.

d. Sufficient real estate is available for location of the reservoir at reasonable economic, environmental, and social costs.

e. The economic value of damageable property protected will justify the cost of modifying the channel.

Table 6-1
Checklist for Channel Modification

Hydrologic Engineering Study Components	✓	Issues
Layout		Determine right-of-way restriction
		Delineate environmentally sensitive aquatic and riparian habitat
		Identify damage centers, delineate developed areas, define land uses for site selection
		Identify infrastructive/utility crossing conflicts
Economics		Determine with-project modifications to stage-discharge function for all conditions
		Determine any downstream effects due to frequency function changes due to loss of channel storage
		Quantify uncertainty in stage-discharge function
		Formulate and evaluate range of channel configurations using risk-based analysis procedures
Performance		Determine expected annual exceedance probability
		Determine expected lifetime exceedance probability
		Describe operation for range of events and analyze sensitivity of critical assumptions
		Describe consequences of capacity exceedances
		Determine event performance
		Formulate OMRR&R plan and prepare O&M manual to include surveillance and flood fighting
Design		Account for ice/debris, erosion/deposition/sediment transport, high velocities
		Evaluate straightening effects on stability
		Evaluate all impact of restrictions/obstructions
Environmental and Social		Evaluate aquatic and riparian habitat impact and identify enhancement opportunities
		Anticipate and identify incidental recreation opportunities

6-3. Channel Overview

Stage in the floodplain is a function of: the channel discharge rate; the channel geometry, including invert slope, cross-sectional area, wetted perimeter, length, and alignment; and the energy "lost" as water is conveyed in the channel. This chapter focuses on measures that reduce out-of-bank stage (and hence, damage) by modifying the geometry or by reducing the energy loss.

a. Channel geometry modification.

(1) The out-of-bank stage can be reduced for a given discharge rate if the channel is modified to increase the effective cross-sectional area. Figure 6-1 shows such a modification. In this elevation versus station plot, the original boundary is shown as a solid line. When the material represented by the shaded polygons is removed, the new boundary is established, as shown. Now the total cross-sectional area beneath the water surface shown is greater than the without-plan area.

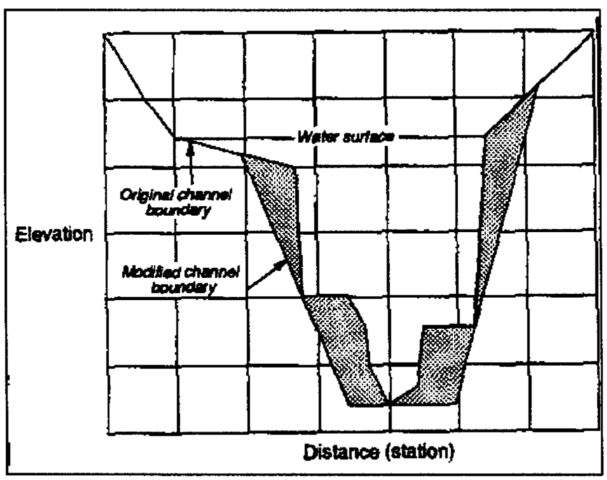

Figure 6-1. Illustration of channel geometry modification

(2) In the simplest case (steady, one-dimensional flow), discharge rate is directly proportional to cross-sectional area. Thus, if all else remains equal, the "improved" channel shown in Figure 6-1 will convey a greater discharge with water surface at the same elevation or the same discharge at a reduced water-surface elevation.

(3) The hydrologic engineering study should recognize that natural channel-geometry modifications may also take place, due to erosion and deposition or to bank instability. In either case, these will affect future with-plan and without-plan conditions. For example, if land-surface erosion increases as a consequence of development in a catchment, this sediment may be deposited in the channel. Without maintenance, this deposition will reduce the cross-sectional area over time, increasing stage for a specified discharge, and increasing EAD for the without-project condition ($E[D_{without}]$ in Equation 2-3). Similarly, scour may cause bank failure, thereby decreasing the effective flow area. This, too, may increase stage and the resulting EAD.

b. Energy loss reduction.

(1) As water is conveyed in a channel, energy is converted from one form to another or "lost." As this loss of energy results in increased stage, stage may be reduced by reducing the energy loss. This may be accomplished by smoothing the channel boundary, straightening the channel, or minimizing the impact of obstructions in the channel.

(2) The variation of water-surface elevation along a stream is largely a function of the boundary roughness and the stream energy required to overcome friction losses (EM 1110-2-1416). If all else remains the same, smoothing the channel to reduce the roughness will reduce the energy loss, which will in turn reduce stage and EAD.

(3) The total energy loss due to friction between two points on a stream is the product of the energy loss per unit length and the distance between the points. Clearly if the stream distance can be reduced, the energy loss and stage may be reduced. Figure 6-2 illustrates how this may be accomplished. The original channel alignment is shown with the gray boundary. The boundary of the realigned channel is dotted. In this case, the energy loss in the improved channel is less and the stage and damage will be reduced. EM 1110-2-1416 explains further that although water-surface profiles are mostly influenced by friction forces, changes in the energy grade line and the corresponding water-surface elevations can result also "... from significant changes in stream velocity between cross sections." These velocity changes may be the result of natural or man-made expansions or contractions in channel width or of bridge crossings in which discharge is forced through an opening smaller than the upstream and downstream channels. To avoid the increase in stage, transitions must be designed carefully, following guidance in EM 1110-2-1416. Similarly, if restricted bridge openings cause stage increases, removal or modification of the bridges should be considered as a feature of the flood-damage-reduction plan.

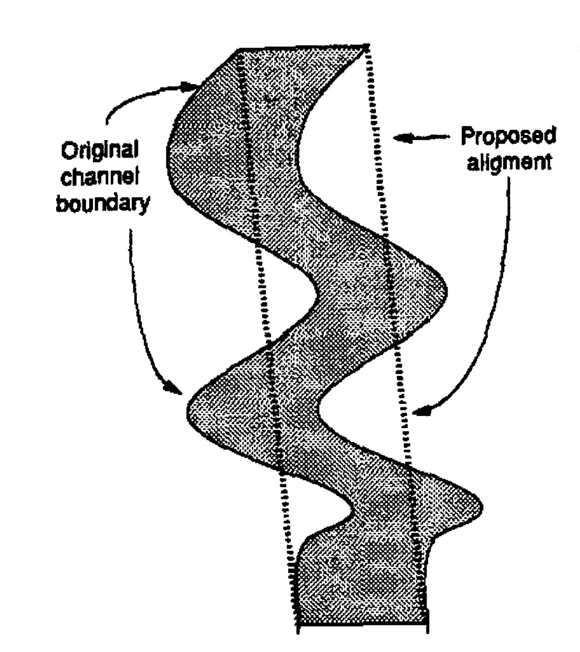

Figure 6-2. Channel re-alignment for damage reduction

6-4. Stage-Reduction Assessment

a. The intended impact of a channel modification is reduction of stage for a given discharge, as illustrated by Figure 6-3. In this figure, the existing, without-plan rating function is shown as a solid line, and the with-plan function is dotted. The modified rating function here shows a lower stage for all discharge values.

b. The impact of a channel modification can be evaluated with river hydraulics models as described in EM 1110-2-1416. These conceptual models have physically based parameters that can reflect the modifications. For example, the HEC-2 computer program, which is described in Appendix B of this manual, includes a model of GVSF. The program uses the physical dimensions of the channel and Manning's *n* (an index of channel roughness) directly to estimate stage. To evaluate the impact of a proposed channel widening, for example, the program input can be modified to reflect the changes. Repeated solution of the GVSF equations for selected discharge rates yields the stage-discharge function for a proposed channel configuration. Likewise, if the proposed plan includes channel smoothing, Manning's *n* value can be changed to reflect this, the program re-run, and the modified-condition rating function determined.

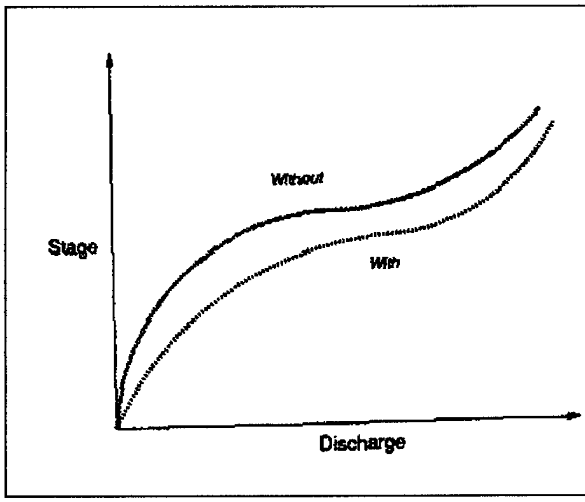

Figure 6-3. Stage-discharge function modifications due to channel improvement

c. Several additional computer programs that embody river hydraulics models appropriate for analysis in other cases are described in Appendix B of this manual and in EM 1110-2-1416.

d. Channel modifications can also affect the discharge-frequency function. In many cases, the modifications will increase velocity in the improved section. Downstream, where no improvements have been made, this will yield greater discharge and, hence, an increase in frequency function quantiles. Further, the channel modifications may eliminate some of the natural storage in the channel. This natural storage, like the storage in a reservoir, would reduce flood peaks. In its absence, the downstream peaks may increase, and this too yields an increase in frequency function quantiles.

6-5. Incidental Impact of Channel Modifications

Channel modifications may also alter the discharge-frequency function if the modifications significantly reduce the timing of the hydrograph through the channel reach. For example, the channel re-alignment illustrated in Figure 6-2 reduces the timing between the upstream and downstream cross sections by reducing its length. This reduction, in turn, may result in an increase in the downstream discharge peak for an event of specified probability. Major channel modifications cause an increase in cross section, as illustrated in Figure 6-1, may increase the storage capacity, and, consequently, reduce the downstream peak for an event of specified probability.

The hydrologic engineer must be aware of the possibility of these incidental impacts, should investigate the change in timing and storage, and must define modified discharge-frequency functions if appropriate.

6-6. Technical Considerations

To ensure that channel modifications yield the damage reduction anticipated, the hydrologic engineer, when formulating and evaluating alternative plans, must give careful consideration to identification and solution of erosion and deposition problems, design for stability (especially if high velocities are anticipated), protection from ice and debris, and provision for on-going OMRR&R.

a. Erosion and deposition.

(1) EM 1110-2-4000 describes the myriad difficulties of sedimentation in rivers and reservoirs. When channel modifications are implemented, some of these problems may worsen. For example, if roughness is decreased, velocity increases, and the likelihood of erosion increases. If deposition was occurring in the without-plan condition, it may or may not continue. Similarly, if a channel is straightened, as shown in Figure 6-2, the stream slope increases, and the potential for deposition increases where the improved reach rejoins the natural alignment downstream, and the potential for scour increases at the transition from the natural reach upstream. Sedimentation studies are required to identify these and other related performance problems.

(2) Design guidance presented in EM 1110-2-1601 identifies the following solutions, which should be considered a part of the plan if necessary to ensure proper performance: (a) stabilizers constructed of grouted or ungrouted rock, sheet piling, or a concrete sill, placed normal to the channel center line, traversing the channel invert, and designed to limit channel degradation; (b) drop structures designed to reduce channel slopes, thus yielding nonscouring velocities; (c) debris basins and check dams to trap and store bed-load sediments.

(3) Channels that convey high velocity (supercritical) flow require special attention. High-velocity channel design must account for the effects of air entrainment, cross waves, superelevation at channel bends, and increased erosion potential. EM 1110-2-1601 provides additional guidance on design of channels.

b. Ice and debris.

(1) Channels in cold regions and channels that carry floating debris (logs and vegetation) can cause special flooding problems. The formation of ice jams and the collection of floating debris at flow constrictions, like bridge crossings, can cause flooding upstream, as the bridge behaves like a dam. The formation of ice jams and the collection of floating debris at flow constrictions also may cause excessive scour due to a local increase in velocity. With such a buildup, the flood discharge must pass through an area that is constricted both laterally and vertically. This leads to increased velocity, which in turn leads to erosion of bed material near the constriction. Likewise, the channel bank in this area might be undermined and ultimately fail.

(2) The hydrologic engineering study must recognize the potential for this, should evaluate system behavior when it does occur, and must design an OMRR&R plan to minimize the likelihood of ice and debris problems. EM 1110-2-1612 describes channel ice formation, ice jams, ice control, and methods for dispersion of floating ice. Similar measures may be required for debris dispersion.

c. OMRR&R. ER 1110-2-1405 requires that a local flood protection project (including channel improvements) include an OMRR&R plan to ensure that the modifications continue to function and provide protection as designed. This feature should provide for continuing inspection of the channel to identify evidence of scour damage to bank protection, significant erosion or deposition of sediment in the channel, and growth of vegetation that will increase resistance, thus increasing stage. The cost of this inspection and the anticipated cost of OMRR&R must be included as a component of the total plan cost.

6-7. Capacity-Exceedance Analysis

As with all proposed flood-damage-reduction plans, the impact of channel capacity exceedance must be evaluated. In the case of channel improvements, this may be accomplished with the appropriate river hydraulics model, using a steady flow or hydrograph with peak that exceeds the selected capacity. The hydrologic engineering study should ensure that topographic data that are assembled for formulation and evaluation include sufficient description of the floodplain outside the channel banks.

6-8. Environmental Impact

Channel modifications can have significant environmental impacts. For example, certain fish species depend on a pool-riffle aquatic environment typical of low flow in a meandering channel. If such a channel is straightened, the habitat will be disrupted, and the change may be lead to reduction in the fish population. The hydrologic engineering analysis should identify such impacts. This will require consultation with environmental specialists. Similarly, consideration must be given to the environmental impact of increased turbidity during construction activities. Potential sources of fine-grained sediment should be identified, and a construction plan should be developed to control runoff from the construction site and to minimize the increase in sensitive areas of the stream.

Chapter 7
Levees and Floodwalls

7-1. Overview

This chapter describes the impact of and hydrologic engineering requirements for planning levees and floodwalls. It also describes interior-area facilities and the requirements for planning those. A checklist of the requirements for formulating and properly evaluating plans is presented as Table 7-1. Because of their unique layout, sizing, and design requirements, a separate checklist is provided for interior areas as Table 7-2.

7-2. Applicability

Levees and floodwalls are effective damage-reduction measures in the following circumstances:

a. Damageable property is clustered geographically.

b. A high degree of protection, with little residual damage, is desired.

c. A variety of property, including infrastructure, structures, contents, and agricultural property, is to be protected.

Table 7-1
Checklist for Levees and Floodwalls

Hydrologic Engineering Study Components	✓	Issues
Layout		Minimize contributing interior runoff areas (flank levees, diversions, collector system)
		Minimize area protected to reduce potential future development per Executive Order 11988
		Investigate levee setback versus height tradeoffs
		Determine right-of-way available for levee/wall alignment
		Minimize openings requiring closure during flood events
Economics		Determine with-project modifications to stage-discharge function for all existing and future conditions
		Quantify uncertainty in stage-damage function
		Formulate and evaluate range of levee and interior area configurations for various capacities using risk-based analysis procedures
		Determine expected capacity/stage exceedance probability
Performance		Determine expected annual exceedance probability
		Determine expected lifetime exceedance probability
		Describe operation for range of events and sensitivity analysis of critical assumptions
		Describe consequences of capacity exceedances
		Determine event performance
		Formulate OMRR&R plan and prepare O&M manual to include surveillance and flood fighting
Design		Design for levee/floodwall superiority at critical features (such as pump stations, high-risk damage centers)
		Design overtopping locations at downstream end, remote from major damage centers
		Provide levee height increments to accommodate settlement, wave run-up
		Design levee exterior erosion protection
		Develop flood warning/preparedness plan for events that exceed capacity
Environmental and Social		Evaluate aquatic and riparian habitat impact and identify enhancement opportunities
		Anticipate and identify incidental recreation opportunities

Table 7-2
Checklist for Interior Areas

Hydrologic Engineering Study Components	✓	Issues
Layout		Define hydraulic characteristics of interior system (storm/drainage system, outlets, ponding areas, etc.)
		Delineate environmentally sensitive aquatic and riparian habitat
		Identify damage centers, delineate developed areas, define land uses for site selection
Economics		Determine with-project modifications to interior stage-frequency function for all conditions
		Quantify uncertainty in frequency function
		Formulate and evaluate range of pond, pump, outlet configurations for various capacities using risk-based analysis procedures
Performance		Determine expected annual exceedance probability
		Determine expected lifetime exceedance probability
		Determine operation for range of events and sensitivity analysis of critical assumptions
		Describe consequences of capacity exceedances
		Determine event performance
		Formulate OMRR&R plan and prepare O&M manual to include surveillance and flood fighting
Design		Formulate/evaluate preliminary inlet/outlet configurations for facilities
		Formulate preliminary operation plans

d. Sufficient real estate is available for levee construction at reasonable economic, environmental, and social costs.

e. The economic value of damageable property protected will justify the cost of constructing the new or enhanced levee and floodwalls.

7-3. Levee and Floodwall Overview

A levee is "... an [earthen] embankment whose primary purpose is to furnish flood protection from seasonal high water and which is therefore subject to water loading for periods of only a few days or weeks a year" (EM 1110-2-1913). Figure 7-1 shows a cross section of a simple levee. A floodwall serves the same purpose under similar circumstances, differing only in the method of construction. It is subject to hydraulic loading on the one side which is resisted by little or no earth loading on the other side. Figure 7-2 shows a variety of floodwalls.

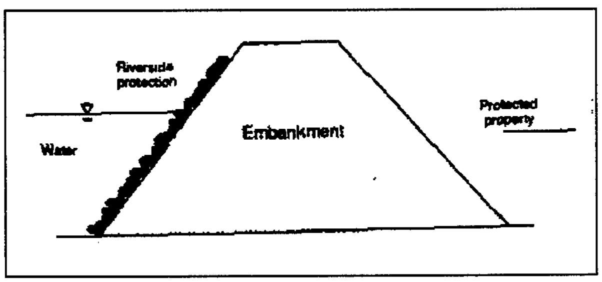

Figure 7-1. Cross section of simple levee

7-4. Flood Damage Reduction Assessment

a. Levees and floodwalls (hereafter referred to as levees for brevity) reduce damage by reducing flood stage in the protected area. They do so by blocking overflow from the channel onto the floodplain. This is represented by a modification to the stage-damage function, as shown in Figure 7-3. S_1 represents the minimum stage, without the levee, at which damage is incurred. The curve represents the remainder of this without-levee function. With the levee in place, the stage at which damage is initially incurred rises to an elevation equal to the height of the levee. This is designated S_2 in the figure. If the water stage rises above this, the levee is overtopped. Then the damage incurred, designated S_2 in the figure, will equal or exceed the without-levee damage.

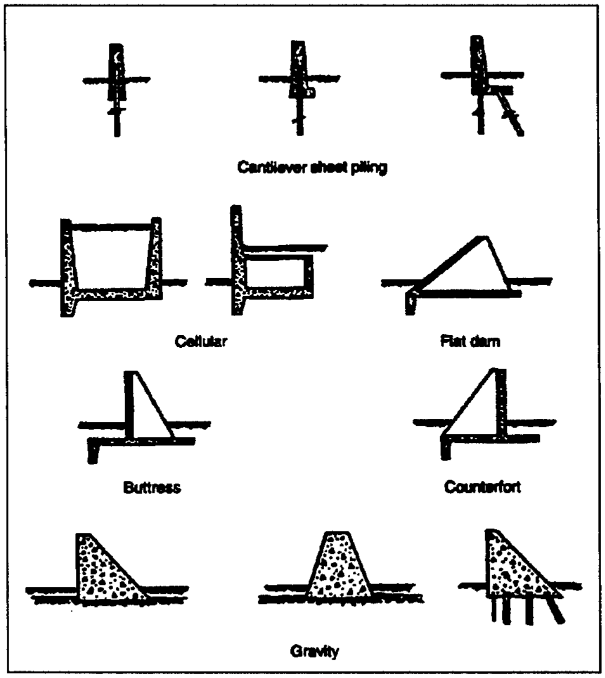

Figure 7-2. Floodwall types. In all cases, water to left, protected area to right

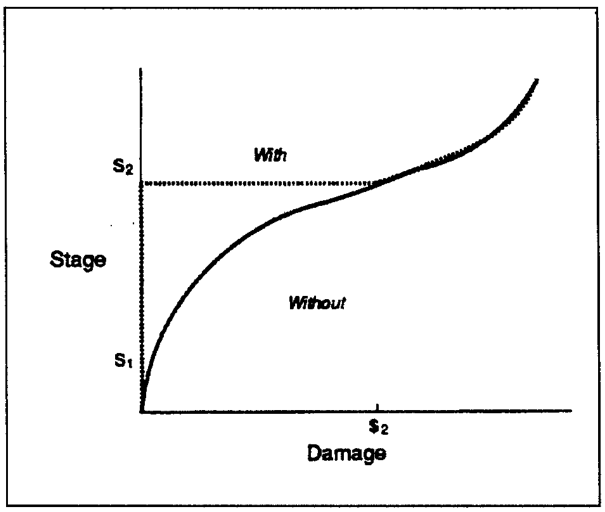

Figure 7-3. Stage-damage function modification due to levee/floodwall

b. A levee may also modify the discharge-frequency function and the stage-discharge relationship. The levee restricts flow onto the floodplain, thus eliminating the natural storage provided by the floodplain. This may increase the peak discharge downstream of the levee for large events that would flow onto the floodplain without the levee. Further, as the natural channel is narrowed by the levee, the velocity may increase. This too may increase the peak discharge for larger events. Modifications to the discharge-frequency function due to a levee are identified with the river hydraulics models or with routing models described in EM 1110-2-1417 and EM 1110-2-1416. These model the impact of storage on the discharge hydrograph and will reflect the loss of this storage. Historical or hypothetical runoff hydrographs can be routed with the selected model to determine discharge peaks with the proposed levee. For example, the modified Puls routing model described in EM 1110-2-1417 uses a relationship of channel discharge to channel storage with the continuity equation to determine the channel outflow hydrograph. A levee will reduce storage for discharge magnitudes that exceed the channel capacity, so the impact will be reflected.

c. Introduction of a levee alters the effective channel cross section, so the levee alters the stage-discharge relationship. The impact of this change can be determined with the river hydraulics models described in EM 1110-2-1416. As with channel alteration, the impact of a levee can be determined by modifying the parameters which describe the channel dimensions. Repeated application of the model with various discharge magnitudes yields the stage-discharge rating function for a specified levee configuration.

7-5. Interior-Area Protection

Figure 7-4 shows an area protected from riverine flooding by a levee. Such a levee (or floodwall) is referred to commonly as the line-of-protection. In this case, the line-of-protection is constructed so natural high ground integrates with the levee to provide the protection; elevation contours shown in the figure illustrate this. The elevation contours also illustrate a problem. The line-of-protection excludes floodwater, but it also blocks the natural flow path of runoff to the river. The protected area, which was formerly flooded by the slow-rising river is now flooded by local runoff, with little warning. This flooding may be only nuisance flooding, or in some cases, it may be flooding that is as dangerous or more dangerous than the riverine flooding. EM 1110-2-1413 describes requirements for interior studies.

a. Solutions to interior flooding problem. To accommodate local runoff, some or all of the facilities shown in Figure 7-5 may be provided. The interior-area runoff is passed through the line-of-protection by a gravity outlet when the interior water level is greater than the

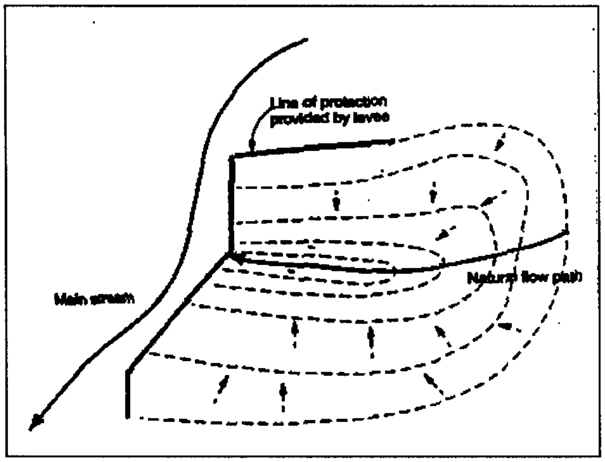

Figure 7-4. Plan view of levee with interior area

exterior level. This outlet may have a gate valve and a flap gate that close to prevent flow from the river into the interior area during high stage. When the exterior stage exceeds the interior stage, interior floodwater is stored in the interior pond and pumped over or through the line-of-protection. This is referred to as a blocked gravity condition.

b. Minimum facility.

(1) Some portion of the interior-area components must be included as a part of any levee plan proposed; these are designated the "minimum interior facility." (See EM 1110-2-1413.) This minimum facility should provide flood protection such that during gravity condition, the local storm-conveyance system functions essentially as it did without the line-of-protection in place, for floods less than the storm-sewer design event. Consequently, the minimum facility often will consist of natural storage and gravity outlets sized to meet local drainage design criteria. If no local storm-sewer system exists, but one is planned, the anticipated design criteria are used for planning the minimum facility.

(2) The minimum facility is intended to be the starting point for planning interior-area protection. According to EM 1110-2-1413, "It is expected that the interior facilities included in the final plan will provide interior area flood relief for residual flooding." However, the incremental benefit of any additional facilities must exceed the incremental cost. This requirement and analysis procedures are described in detail in EM 1110-2-1413.

c. Analysis.

(1) Hydrologic analysis of interior area behavior is complex because of the interaction of the interior and exterior waters. EM 1110-2-1413 describes three interior-area analysis methods. These are summarized in Table 7-3. The analysis approach chosen is based on available resources, available data, and technical knowledge. The decision should be made when the HEMP is

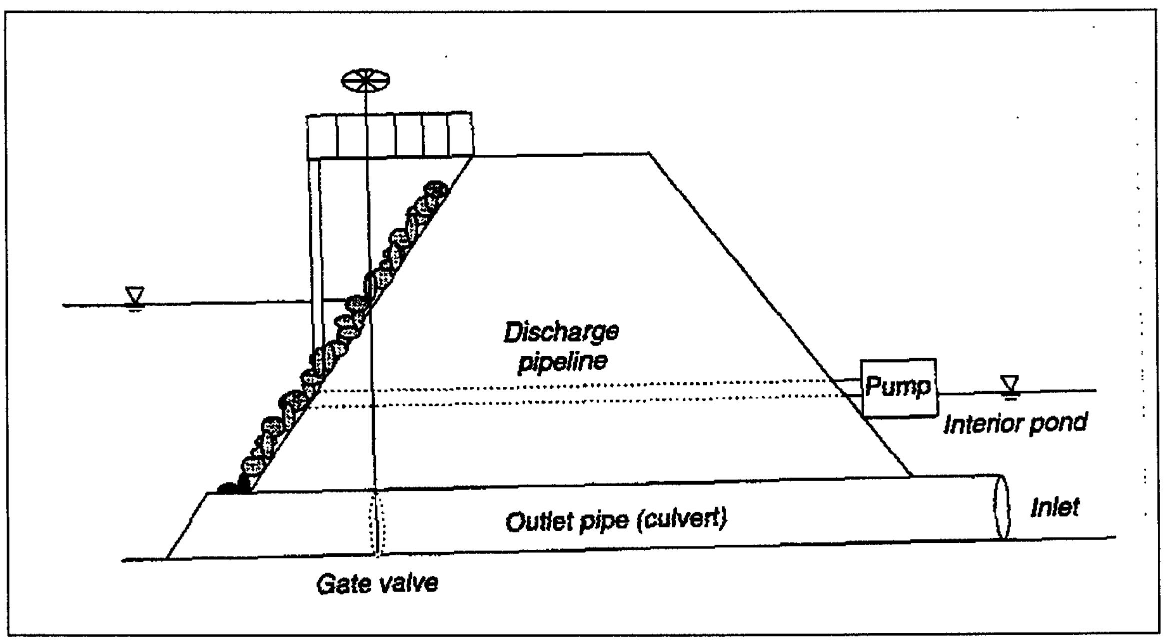

Figure 7-5. Components of interior-area protection system

Table 7-3
Interior-Area Analysis Alternative (from EM 1110-2-1413)

Method	Summary
Continuous record simulation	Simulate without-project and with-project conditions with continuous records of exterior and interior hydrology. These records may be historical flows or flows defined with "streamflow generation" techniques. Use runoff-routing models with recorded rainfall if necessary to estimate discharge. Simulate pond, outlet, pump operation for period. Develop necessary stage-frequency functions, duration estimates for economic analysis.
Discrete historical or hypothetical event simulation	Develop stage-frequency function for exterior with event simulation flood events that have an effect on interior flooding when interior flooding occurs coincidentally. Simulate without-plan and with-plan conditions for interior area with discrete historical or hypothetical events for low exterior stages that do not affect interior flooding. Develop interior stage-frequency function. Combine the two stage-frequency functions using the joint-probability theorem.
Coincident frequency analysis	For situations in which occurrence of exterior and interior flooding is independent, apply total probability theorem to define stage-frequency functions. To do so, develop exterior stage-frequency function, simulate system performance to develop interior frequency function for various exterior stages, combine functions.

developed. (See paragraph 1-7 of this manual for a description of the HEMP.)

(2) The HEC-IFH computer program (USACE 1992b), which is described in Appendix B, is specifically designed for the simulation required for interior-area analysis.

7-6. Design Exceedance

a. The principal causes of levee failure are (1) internal erosion, known as piping; (2) slides within the levee embankment or the foundation soils; (3) overtopping; and (4) surface erosion. The hydrologic engineering study must integrate geotechnical engineering elements to guard against failures due to piping and slides; flow nets may be required to provide sufficient information for proper design.

b. The likely locations and impact of levee overtopping must be addressed. This is a particularly difficult task, because the hydraulics problem created by levee overtopping is a multi-dimensional, unsteady flow problem. Further, when a levee is overtopped, it may breach, so complete analysis also includes the components of a dam-failure analysis. Nevertheless, information on the impact of the failure, including estimates of extent of the inundated area, warning time, and property and lives at risk must be determined. An unsteady fluvial-process model may provide information necessary for this analysis.

c. Surface erosion cannot be eliminated completely, but if proper precautions are taken, the likelihood of levee failure due to this can be minimized. EM 1110-2-1913 offers specific guidance in protecting riverside slopes; Table 7-4 summarizes this guidance.

7-7. Other Technical Considerations

Most levee projects and some interior-area protection schemes are designed to operate automatically and only require surveillance of operation during floods. A complete plan will include provisions for this surveillance and for flood-fighting activities, which involve special precautions to ensure the safety and integrity of levees. EM 1110-2-3600 notes that "It is important that managers of water control systems be properly appraised of the status of levee projects in conjunction with the overall control of a water resource system." This will ensure that gates are opened or closed properly, pumps are turned on or off as necessary, and access openings in the levee or floodwall are closed properly in anticipation of rising floodwater.

Table 7-4
Methods of Protecting Levee Riverside Slopes (from EM 1110-2-1913)

1. If duration of flooding is brief, provide grass protection, unless currents or waves act against levee.

2. Provide additional protection if embankment materials are fine-grained soils of low plasticity (or silts), as these are most erodible.

3. If severe wave attack and currents are expected, shield riverside slope timber stands and wide space between riverbank and levee.

4. Take care to accommodate scour due to flow constrictions and turbulence caused by bridge abutments and piers, gate structures, ramps, and drainage outlets.

5. To minimize turbulence and susceptibility to scour, avoid short-radius bends and provide smooth transitions where levees meet high ground or structures.

6. Depending on degree of protection needed and relative costs, provide slope protection with grass cover, gravel, sand-asphalt paving, concrete paving, articulated concrete mat, or riprap.

Chapter 8
Other Measures That Reduce Existing-Condition Damage Susceptibility

8-1. Overview

Existing-condition damage susceptibility, and hence EAD, can be reduced with so-called "nonstructural" measures described in this chapter. The measures include floodproofing, relocation, and flood-warning/preparedness (FW/P) plans. Requirements for the measures are summarized in Table 8-1.

8-2. Requirements for Floodproofing

a. Applicability. Floodproofing measures are appropriate for damage reduction for single-story, residential structures. In special cases, these measures have been used for other structures, but the economic and physical feasibility of such applications is limited. Floodproofing does not reduce damage to utilities, infrastructure, lawns, and other exterior property. These measures are limited generally to property frequently flooded. Floodproofing is generally less disruptive to the environment than other measures that require significant construction.

b. Overview of floodproofing.

(1) Floodproofing includes (a) use of closures and small walls to keep out floodwaters and (b) raising existing structures in-place to reduce damage. The measures are spatially distributed, so do not provide the same uniform protection possible with, for example, a reservoir. Floodproofing reduces damage to existing individual structures or parcels of land by altering damage susceptibility.

(2) Closures, like those shown in Figure 8-1, reduce damage by keeping the floodwater out of the structure. This figure shows window closures, but similar closures can be provided for doors and other openings. Closures may be temporary or permanent. The figure shows temporary closures; these are bolted into place during a flood threat and removed afterwards. In addition to the closures, depending on site conditions, the following may be required: a waterproofing sealant applied to the walls and floors to reduce seepage, a floor drain and sump pump to accommodate seepage, and a valve to eliminate flooding in the structure due to sewer backflow.

(3) Similar damage reduction can be achieved with a small wall or levee built around one or several structures. Such a wall is designed for compatibility with local

Table 8-1
Checklist for Measures that Reduce Existing-Condition Damage Susceptibility

Hydrologic Engineering Study Components	✓	Issues
Layout		Based on qualification of flood hazard, identify structures for which measures are appropriate
Economics		Determine with-project modifications to stage-damage function for all existing and future conditions
		Quantify uncertainty in stage-damage function
		Formulate and evaluate range of floodproofing, relocation, and/or FW/P plans, using risk-based analysis procedures
Performance		Determine expected annual exceedance probability
		Determine expected lifetime exceedance probability
		Determine operation for range of events and sensitivity analysis of critical assumptions
		Describe consequences of capacity exceedances
		Determine event performance
		Formulate OMRR&R plan and prepare O&M manual to include surveillance and flood fighting
Design		Develop, for all these measures, FW/P plans
Environmental and Social		Evaluate aquatic and riparian habitat impact and identify enhancement opportunities
		Anticipate and identify incidental recreation opportunities

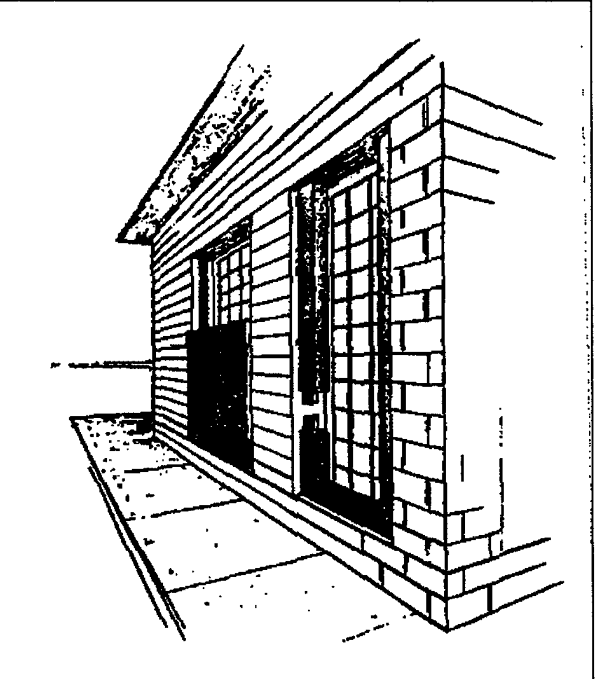

Figure 8-1. Floodproofing with closures (from USACE 1978)

landscaping and aesthetics, and generally is less than 1 meter high. Walls may be brick, stone, concrete, or some other material designed to withstand lateral and uplift forces associated with floodwaters. As with a major levee, runoff in the interior area must be managed; often a small pump is adequate.

(4) Figure 8-2 shows an existing structure after it was raised in-place to reduce damage. The hazard is not eliminated here, but the damage is reduced. Now when a flood occurs, the depth of water at the site, relative to the original ground level, is the same, but the depth of flooding in the structure is less. In Figure 8-2, the structure is a single-story wooden-frame residential structure that was constructed originally with a crawl space and no basement. Specific actions required to raise this structure are listed in Table 8-2. While it is possible to raise almost any structure, raising a structure such as that illustrated is most likely to be economically justified and physically feasible. Note that in the figure, fill was used to raise the car-parking pad.

c. Flood damage reduction assessment.

(1) Floodproofing alters the stage-damage relationship for structures. The manner in which it does so

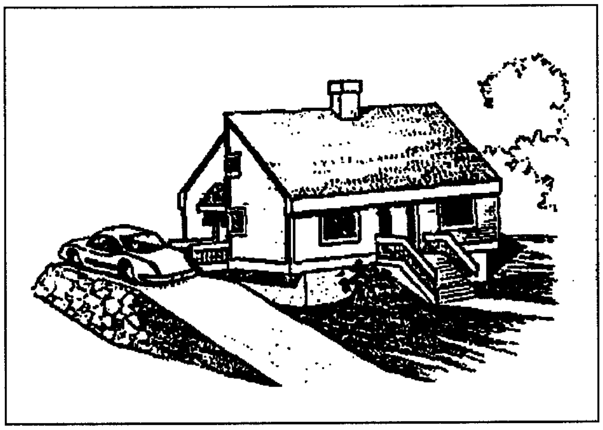

Figure 8-2. Floodproofing by raising an existing structure in-place (from U.S. Dept. of Housing and Urban Development 1977)

Table 8-2
Actions Required to Raise a Structure In-Place (from USACE 1978)

1. Disconnect all plumbing, wiring, and utilities that cannot be raised with the structure.

2. Place steel beams and hydraulic jacks beneath the structure and raise to desired elevation.

3. Extend existing foundation walls and piers or construct new foundation.

4. Lower the structure onto the extended or new foundation

5. Adjust walks, steps, ramps, plumbing, and utilities. Regrade site as desired.

6. Reconnect all plumbing, wiring, and utilities.

7. Insulate exposed floors to reduce heat loss and protect plumbing, wiring, utilities, and insulation from possible water damage.

depends on the measures used. Figure 8-3 illustrates the alteration when a closure or small wall is used. The existing condition, without-project stage-damage function is the solid line curve; the modified function is the dotted curve. Without the closure or wall, damage begins when stage reaches S_1, as shown in the figure. With the closure or wall in place, the onset of damage is raised to stage S_2. Of course, if the stage exceeds S_2, the closure or wall is overtopped, and damage is essentially that which would be incurred without the measure. In the figure, this is represented by the sharp increase in with-project damage for stage greater than S_2.

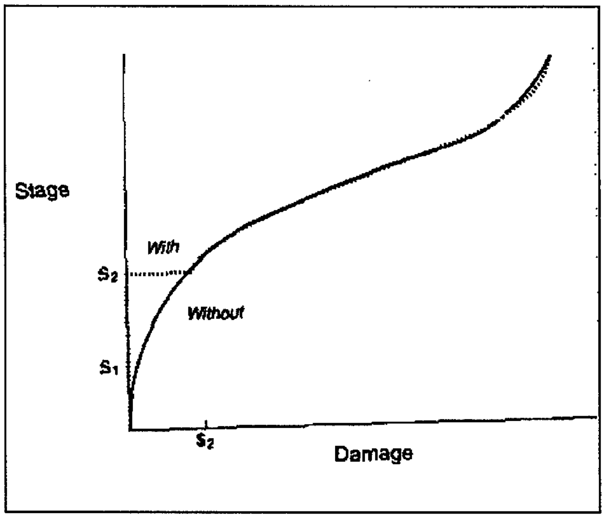

Figure 8-3. Stage-damage function modification due to floodproofing with closure, wall

(2) Figure 8-4 illustrates the alteration when an existing structure is raised in-place. Again, the existing condition, without-project stage-damage function is the solid line curve, and the modified function is the dotted curve. For the existing, without-project condition, damage begins when stage reaches S_1. When the structure is raised, the stage-damage function is shifted upward a distance equal to the increased elevation, but the function retains essentially the same shape. Thus the onset of damage is raised to stage S_2, and the damage incurred at all stages equals the damage previously incurred at that stage less the distance the structure was raised.

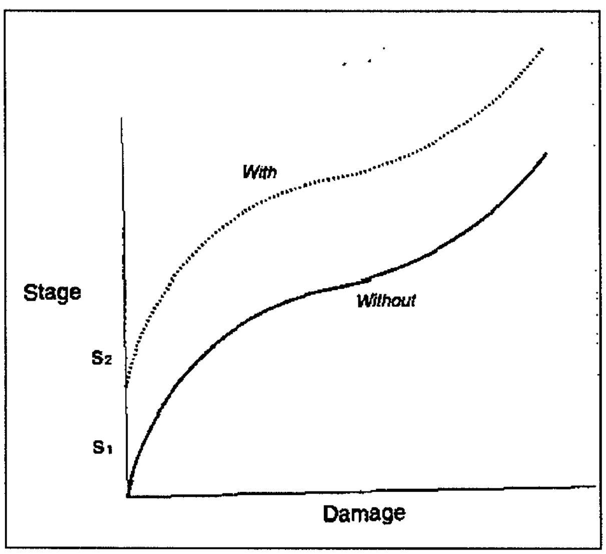

Figure 8-4. Stage-damage function modification due to floodproofing by raising in-place

d. Technical considerations.

(1) Reports from HEC (USACE 1978, 1985) describe various nonstructural measures in detail and identify critical technical considerations for formulating plans that include these measures. Some of the important considerations identified there are summarized in Table 8-3.

Table 8-3
Performance Requirements for Floodproofing

Floodproofing Method	Performance Requirement
Window or door closure	Provide adequate forecasting and warning to permit installation of closures.
	Identify *all* openings for closure, including fireplace cleanouts, weep holes, etc.
	Ensure structural adequacy to prevent failure due to hydrostatic pressure or floating of structure.
	Ensure watertightness to minimize leakage.
	Arrange adequate, on-going public training to ensure proper operation.
Small wall or levee	Requirements similar to those for major levee, but on a smaller scale, including (1) providing for closure of openings in wall or levee; (2) ensuring structural stability of levee or wall; providing for proper interior drainage.
	Arrange adequate, on-going public training to ensure proper operation.
	Plan for emergency access to permit evacuation if protected area is isolated by rising floodwaters.
Raising in place	Protect beneath raised structure, as hazard is not eliminated.
	Ensure structural stability of raised structure.
	Plan for emergency access to permit evacuation if protected area is isolated by rising floodwaters.

(2) A critical task is to characterize floods to permit design of alternative measures that satisfy the performance constraints. In doing so, estimates of depths, velocities, and sediment and debris loads of flowing water, and the forces due to these must be provided. The fluvial- and

alluvial-process models described in Appendix B may provide the necessary information.

(3) A complete plan that incorporates floodproofing must include an emergency evacuation plan. This can only be formulated properly by using hydrologic engineering input. Inundated areas for identifying escape routes and estimating flow velocities for evaluating the safety of the evacuation routes must be identified. For example, if a small 2-foot-high levee is proposed for a group of residences, the velocities associated with flows corresponding to depths greater than 2 feet should be determined and the likelihood of evacuation by foot, vehicle, or boat evaluated.

8-3. Requirements for Relocation

a. Applicability. Relocating contents within an existing structure at its current location is effective in any case, but the damage reduction possible is limited. The residual damage is likely to be great. Permanently removing the contents or the structure and contents from a flood hazard area similarly reduces damage in any case, but is likely to be costly and, thus, economically feasible only for higher value structures. Permanent relocation is physically feasible for a limited class of structures (USACE 1978).

b. Overview of relocation.

(1) The term relocation, as used in this manual, means moving property so it is less susceptible to damage. This may be accomplished by (a) relocating contents within an existing structure at its current location or (b) removing the contents or the structure and contents from a flood hazard area.

(2) Examples of relocation of contents within a structure are shown in Table 8-4. These are relatively simple measures that can be undertaken by any property owner. The relocation can be temporary or permanent. Effectiveness depends on the type of contents and flood hazard.

Table 8-4
Examples of Relocation (from USACE 1978)

1. Protecting HVAC equipment, appliances, shop equipment by raising off floor.

2. Relocating property to higher floors.

3. Relocating commercial and industrial products, merchandise, equipment to higher floor or higher building.

4. Relocating finished products, materials, equipment, other movable items now located outside to higher ground.

5. Protecting electrical equipment by raising on pedestal, table, platform.

6. Anchoring property that might be damaged by floodwater movement.

(3) Removing contents or a structure is an effective, if costly, solution to the flood-damage problem in any circumstance. To accomplish this, a building site outside the flood hazard area must be located and purchased or leased. In the case of moving a structure, the new site must be prepared; the structure must be raised, transported, and installed at the new site; contents must be moved; and the old site restored. For relocating contents only, a structure outside the hazard area must be built or leased, and contents must be moved.

c. Flood damage reduction assessment. Relocation reduces flood damage by reducing the damage incurred at a given stage. In the extreme, if all structures and their contents are moved from the flood hazard area, the stage-damage function is reduced to zero damage for all stages in the range of practical interest. More practically, if selected structures or contents are relocated, the stage-damage function will be modified to reflect the lowered value of property that would be inundated at a given elevation. In general, the damage for a specified stage will be reduced; the exact form of the modified with-project stage-damage function depends on location and value of property relocated.

d. Technical considerations.

(1) Hydrologic engineering plays a critical role in formulating relocation plans. Properties subject to inundation and reduced-hazard elevations to which contents must be moved or sites to which structures should be moved must be identified. If a significant number of structures or goods stored outside are moved, the hydraulic properties of the floodplain may change, and the impact using alluvial or fluvial process models, such as those described in Appendix B, must be assessed.

(2) If relocation of contents is a temporary flood damage reduction measure, the plan must include a forecast and warning component. The requirements are presented in paragraph 8-4.

8-4. Requirements for Flood Warning-Preparedness Plans

a. Applicability. A FW/P program may be implemented as (1) a stand-alone measure when other measures are not feasible, (2) an interim measure until others are in-place, or (3) a component of other measures. FW/P as a stand-alone measure provides only minimum damage reduction. Even with the most efficient forecast and best-planned response system, the possibility of significant damage continues to exist in a managed manner. A FW/P plan has no significant environmental impact in most cases.

b. Overview of flood warning and preparedness plans.

(1) A FW/P plan reduces flood damage by providing the public with an opportunity to act before stages increase to damaging levels. The savings due to a FW/P plan may be due to reduced inundation damage, reduced cleanup costs, reduced cost of disruption of services due to opportunities to shut off utilities and make preparations, and reduced costs due to reduction of health hazards. Further, FW/P plans may reduce social disruption and risk to life of floodplain occupants.

(2) A FW/P plan is a critical component of other flood damage reduction measures, as pointed out elsewhere in this manual. In addition, the Corps Flood Plain Management Services (FPMS) staff may provide planning services in support of local agency requests for assistance in implementation of a FW/P plan; this is authorized by Section 206 of the Flood Control Act of 1960.

c. Flood damage reduction assessment. A FW/P plan reduces inundation damage by permitting the public to relocate property, close openings, close backflow valves, turn on sump pumps, and take other actions that will lower the damage incurred when water reaches a specified stage. Estimating the form of the modified, with-project stage-damage function requires estimating the accuracy of a forecast and how the public will respond to a warning. Day (1973) suggested a method for estimating the benefit, but the hydrologic engineering study should make estimates appropriate for each particular application.

d. Technical considerations. Table 8-5 shows the components of a complete FW/P plan. If the plan is to function properly, it must include each of these components. Formulation and subsequent design of the flood threat recognition subsystem is part of the hydrologic engineering study. Likewise formulation of the emergency-response plan requires information from the hydrologic engineering study as does delineation of inundated areas and identification of escape routes. USACE (1986) provides guidance.

Table 8-5
Components of a FW/P System (adapted from USACE 1988a)

Component	Purposes
Flood-threat-recognition subsystem	Collection of data and information; transmission of data and information; receipt of data and information; organization and display of data and information; prediction of timing and magnitude of flood events.
Warning-dissemination subsystem	Determination of affected areas; identification of affected parties; preparation of warning messages; distribution of warning messages.
Emergency-response subsystem	Temporary evacuation; search and rescue; mass care center operations; public property protection; flood fight; maintenance of vital services.
Postflood recovery subsystem	Evacuee return; debris clearance; return of services; damage assessment; provisions for assistance.
Continued system management	Public awareness programs; operation, maintenance, and replacement of equipment; periodic drills; update and arrangements.

Chapter 9
Measures That Reduce Future-Condition Damage Susceptibility

9-1. Overview

Future-condition damage may be reduced through land-use and construction regulation or by acquisition. Although neither is used commonly in Corps flood damage reduction plans, both are potentially components of a complete plan in which costs are shared with local partners. Consequently, requirements for these measures are described in this chapter. The checklist included in Chapter 8 describes requirements for measures described in this chapter.

9-2. Requirements for Construction and Land-Use Regulation

a. Overview.

(1) Construction and land-use regulation includes building codes, zoning ordinances, and subdivision regulations. These measures decrease future damage by reducing susceptibility of future development.

(2) Figure 9-1 illustrates the result of one form of construction regulation. In this case, the building code requires that the lowest floor of new construction be above the 1 percent chance flood stage. To comply, this structure is built on timber posts. This type of construction, of course, does not control the flood stage, but it does reduce the damage incurred. Construction on concrete walls, on steel, concrete, or masonry posts, piles, or piers, or on earth fill will have similar impact.

(3) Damage susceptibility of new structures can be reduced also by regulating construction materials and practices. Table 9-1 lists typical requirements that may be included in such regulations.

(4) Finally, future damage susceptibility can be reduced with land-use regulations that ensure that future use of floodplains is compatible with the hazard there. Zoning permits district-by-district regulation of "... what uses may be conducted in flood hazard areas, where specific uses may be conducted, and how uses are to be constructed or carried out (USWRC 1971)." Subdivision regulations "... guide division of large parcels of land into smaller lots for the purpose of sale of building developments ... [they] often (a) require installation of adequate drainage facilities, (b) require that location of flood hazard areas be shown on the plat, (c) prohibit encroachment in floodway areas, (d) require filling of a portion of each lot to provide a safe building site at elevation above selected flood heights or provide for open support elevation to achieve the same ends, and (e) require the placement of streets and public utilities above a selected flood protection elevation (USWRC 1971)."

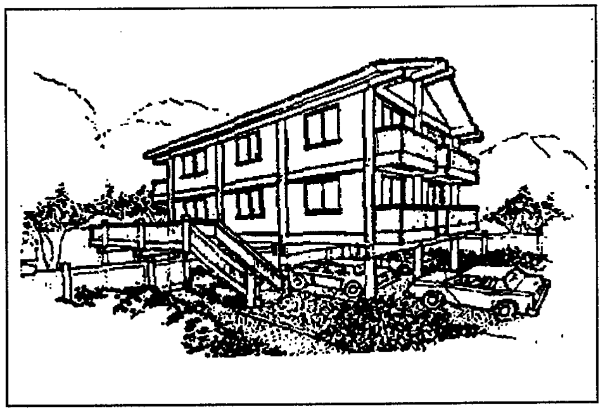

Figure 9-1. Illustration of construction per regulations to reduce damage susceptibility (from U.S. Dept. of Housing and Urban Development 1977)

b. Flood damage reduction assessment: future, with-project evaluation. Paragraph 2-3*b* explains computation of EAD and describes how, if conditions change over time, EAD is to be computed annually and discounted to determine an equivalent annual value over the life of a plan. Land-use and construction regulations will yield changes in the future-condition stage-damage function, thus reducing this equivalent annual value. This is illustrated by Figure 9-2. This figure shows EAD computed over a period of 50 years. Without regulations, the value continues to increase each year as the value of development subject to flood damage increases. If construction and land-use regulations are imposed in 1999, however, the EAD stops increasing. Due to the regulations, the value of property exposed to flood damage does not increase beyond the 1999 level. In fact, if regulations prohibit new construction that is susceptible to flood damage, the EAD may decrease as structures and contents reach the end of their useful life and are replaced with structures and contents less susceptible to flood damage.

c. Technical considerations. To some degree, construction and land-use regulations are applicable in all floodplains. To ensure success, the hydrologic engineering studies are required in delineating the hazard area and characterizing the flooding. The delineation is necessary

Table 9-1
Typical Requirements for New Construction to Reduce Damage Susceptibility (from USACE 1978)

Location	Requirement
Basement	Install drains, valves to equalize water pressure
	Use permeable backfill
	Use water-resistant flooring
	Use moisture tolerant paints and paneling
	Provide ceiling drains to permit drywall drainage
	Provide anchored, water-resistant cabinets
	Construct stairways sufficiently wide for relocation of basement contents
First floor	Use water-resistant paints, paneling, flooring
	Provide cabinets, bookshelves, furnishings that are moisture tolerant
	Provide stairways sufficiently wide for relocation of first-floor contents
Exterior	Anchor tanks to prevent floatation, vent above first floor to prevent fuel escape
	Provide manually operated sewer backflow valves.
	Use nonabsorbent, exterior-grade materials and treated lumber.
Electrical, heating, cooling system	Provide duct drains
	Separate electrical circuits to allow selective shutoff
	Slope gas piping, fit with drains

to identify property to which regulations should apply, and the characterization is necessary to determine the nature of the regulations.

9-3. Requirements for Acquisition

a. Overview. Public acquisition of floodplain property is another method by which the government, either Federal or local, can ensure proper use, thus reducing damage susceptibility. Title to the property can be acquired, or a land-use easement can be acquired. In the first case, ownership of the property shifts to the public, so uses with high risk of damage can be abandoned. Instead, the property can be dedicated to use as a park or wildlife preserve. Acquisition of a land easement leaves property in the hands of private owners, but permits restriction of use. For example, building or filling within an easement can be prohibited.

b. Flood damage reduction assessment: future, with-project evaluation. Acquisition has an impact similar to that of construction and land-use control: It reduces future damage. Figure 9-2 might well illustrate the EAD with acquisition of floodplain property in 1999, as this too will reduce susceptibility to damage, and hence EAD, thereafter.

c. Technical considerations. Again, hydrologic engineering plays a critical role in formulating acquisition plans. The flood-hazard area is delineated to permit identification of land that should be acquired. The change in floodplain development may ultimately alter the hydraulic properties of the channels resulting in the necessity of redefining stage-discharge relationships for the time period following acquisition.

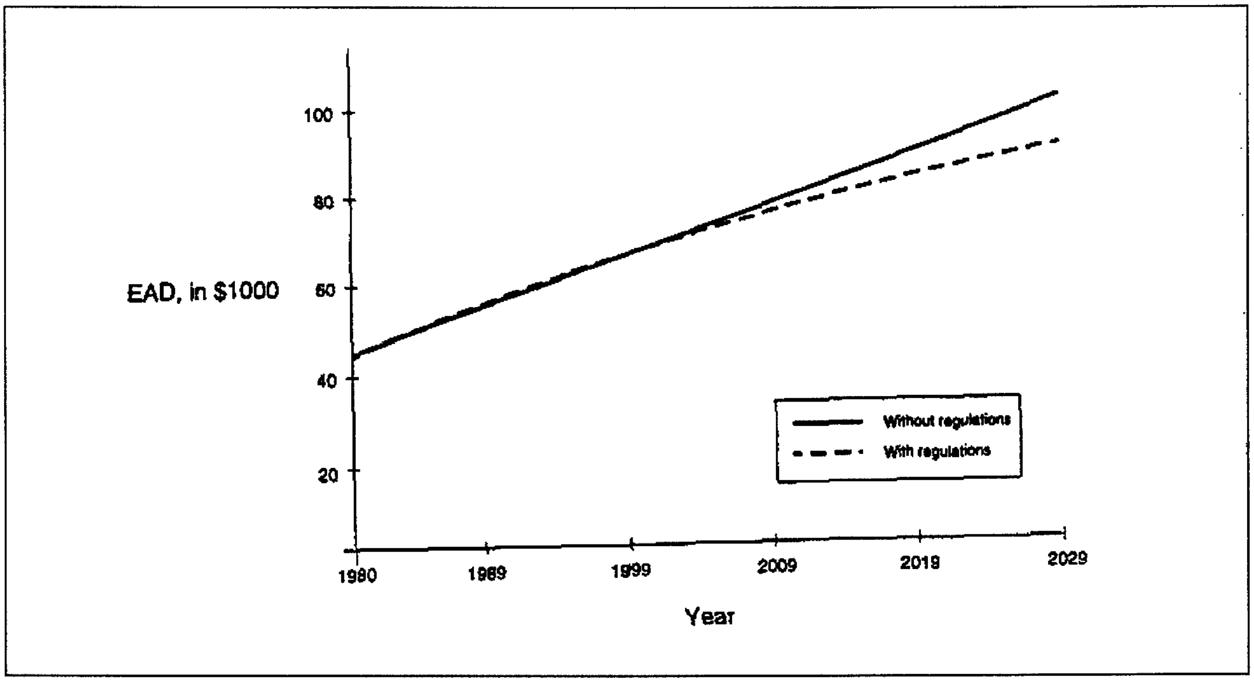

Figure 9-2. Illustration of regulation impact on future-condition EAD

Chapter 10
System Analysis

10-1. Plan Evaluation

a. Plans for reducing flood damage are comprised of one or more type of measures. For example, a mix of channel modifications, detention storage, floodproofing, regulatory policies, and flood-warning preparedness may be one plan for reducing flood damage throughout the study area. Another plan may have similar mixes of measures but is sized differently and may be used at different locations. Other plans may be completely different sets of measures and actions. The plan formulation and evaluation process is summarized in Chapter 2 and discussed in detail in ER 1105-2-100.

b. The total economic accomplishment, performance, and environmental impact of a flood damage reduction plan is not simply the sum of the output of the individual measures. Instead, a well-formulated plan can yield greater benefit, perform better, and have less adverse impact through synergism. For example, if land-use regulation is combined with a reservoir, the flow regulations will reduce damage susceptibility and the size of a reservoir may be reduced. Consequently, the same damage reduction may be achieved at less cost and, perhaps, with less adverse environmental impact. This interaction means that the components of a plan cannot be formulated and evaluated independently. Instead, the interdisciplinary planning team must view a flood damage reduction plan as a system and must evaluate explicitly the interactions of the measures. These interactions will affect the economic benefit performance, and environmental impact of the plan.

10-2. Economic-Objective Evaluation for System

a. The impact of interaction of plan components can be illustrated with the example in Figure 10-1. For this example, development upstream has led to increased runoff that in turn, causes flood damage downstream. The planning team has proposed a channel modification to reduce the downstream stage and corresponding damage. Based on engineering judgment and experience, several alternative sizes and configurations were proposed. In response to concern over the environmental impact of excavation required for larger channels, an upstream detention storage basin also has been proposed. This detention basin, configured as shown, reduces the flow to the channel, thus reducing the required capacity and the necessary excavation. Again based on engineering judgment and experience, several alternative sizes and configurations were proposed for the detention basin.

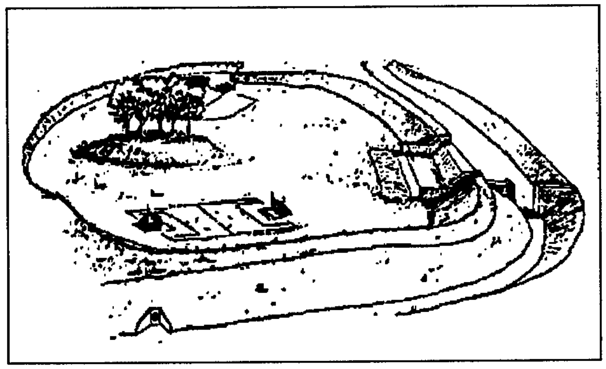

Figure 10-1. Example of flood damage reduction system (from drawing furnished by U.S. Army Engineer District, Tulsa)

b. To evaluate the net benefit of each alternative, the interaction of the channel and the detention basin must be considered explicitly, since the channel impacts the stage-discharge function and detention storage impacts the discharge-frequency function. To do so systematically, a decision tree like that shown in Figure 10-2 might be constructed to identify the plans. In this illustration, four channel sizes and configurations are formulated; these are labeled C1, C2, C3, and C4. Three detention storage alternatives, labeled D1, D2, and D3, are proposed. Each branch in the decision tree represents an alternative plan with one of the proposed channel configurations and one of the proposed detention storage alternatives. Evaluation of the with- and without-project conditions

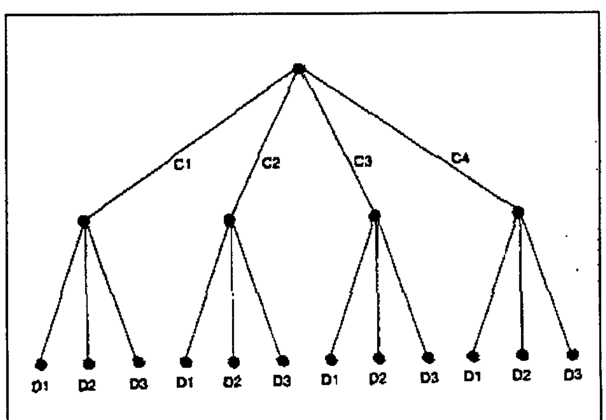

Figure 10-2. Decision tree for system of Figure 10-1

frequency and stage relationships using procedures are described in Chapter 2. The expected annual damage analyses are performed as illustrated in Figure 2-1.

c. The hydrologic engineering studies must identify both planned and incidental changes to the discharge-frequency, stage-discharge, and stage-damage functions. Table 10-1 summarizes both for various flood damage reduction measures described in this manual, but the list is not universal. A careful analyst will consult the Corps laboratories and experienced staff for help with identifying interactions in unusual circumstances.

Table 10-1
Impacts of Flood Damage Reduction Measures

	Impact of Measure		
Measures	Modifies discharge-frequency function	Modifies stage-discharge function	Modifies stage-damage function
Reservoir	Yes	Maybe, if stream and downstream channel erosion and deposition due to change in discharge occur	Maybe, if increased development in floodplain occurs
Diversion	Yes	Maybe, if channel erosion/deposition due to change in discharge occur	Maybe, if increased development in floodplain occurs
Channel improvement	Maybe, if channel affects timing and storage is altered significantly	Yes	Not likely
Levee or floodwall	Maybe, if floodplain storage is no longer available for flood flow	Not likely	Yes
Floodproofing	Not likely	Not likely	Yes
Relocation	Not likely	Maybe, if flow obstructions are removed	Yes
FW/P plan	Not likely	Not likely	Yes
Land-use and construction regulations	Not likely	Maybe, if flow obstructions are removed	Yes
Acquisition	Not likely	Maybe, if flow obstructions are removed	Yes

Appendix A
References

A-1. Required Publications

Flood Control Act of 1960

Federal Water Pollution Control Act

Executive Order 11988, Flood Plain Management
Code of Federal Regulation, 40 Part 230

CECW-E/CECW-P/CECW-L Memorandum
Planning, Engineering, and Design Process, General Design Memoranda, and Re-evaluation Reports

ER 200-2-2
Procedures for Implementing NEPA

ER 1105-2-100
Guidance for Conducting Civil Works Planning Studies

ER 1110-2-401
Operation, Maintenance, Repair, Replacement, and Rehabilitation Manual for Projects and Separable Elements Managed by Local Sponsors

ER 1110-2-1150
Engineering and Design for Civil Works Projects

ER 1110-2-1405
Hydraulic Design for Local Flood Protection Projects

ER 1110-2-1450
Hydrologic Frequency Estimates

ER 1110-8-2 (FR)
Inflow Design Floods for Dams and Reservoirs

EP 1110-2-8
Explaining Flood Risk

EP 1110-2-9
Hydrologic Engineering Studies Design

EP 1110-2-10
Hydrologic Engineering Analysis Concepts for Cost-Shared Flood Damage Reduction Studies

EP 1165-2-1
Digest of Water Resources Policies

EM 1110-2-1411
Standard Project Flood Determinations

EM 1110-2-1413
Hydrologic Analysis of Interior Areas

EM 1110-2-1415
Hydrologic Frequency Analysis

EM 1110-2-1416
River Hydraulics

EM 1110-2-1417
Flood-runoff Analysis

EM 1110-2-1601
Hydraulic Design of Flood Control Channels

EM 1110-2-1602
Hydraulic Design of Reservoir Outlet Works

EM 1110-2-1603
Hydraulic Design of Spillways

EM 1110-2-1612
Ice Engineering

EM 1110-2-1913
Design and Construction of Levees

EM 1110-2-2502
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Appendix B
Commonly Used Computer Models for Corps Flood Damage Reduction Studies

B-1. Introduction

This appendix describes Corps-developed computer models that are used commonly in flood damage reduction planning studies. These models simulate critical processes and provide information necessary to evaluate the economic objective function and to confirm satisfaction of the environmental-protection and performance constraints.

a. Definitions. For clarity, the description herein makes a distinction between mathematical models, computer models (also called programs), and applications. A mathematical model is a symbolic representation of the behavior of a system. For example, the combination of the continuity and momentum equations is a mathematical model of flow in an open channel. To yield information, the equations of a mathematical model must be solved. If the equations are relatively simple, they may be solved with pencil and paper and electronic calculator. For example, the equations of the unit-hydrograph model can be solved in this fashion to predict runoff from a simple rainstorm. On the other hand, if the equations included in the model are too numerous or too complex to solve with pencil, paper, and calculator, they may be solved instead by translating the equations and an appropriate equation solver into computer code. The result is a computer model or computer program. When the equations of a mathematical model are solved with site-specific initial and boundary conditions and parameters, the model simulates the processes and predicts what will happen to the particular system. This solution with specified conditions is an application of the model. An application may use a computer model, or it may use the mathematical model with solution with pencil, paper, and calculator.

b. Selecting a model. Ford and Davis (1989) write that water-resources planning and management is similar to home improvement: In both, the appropriate tool must be selected to solve the problems at hand. In the case of home improvement, the decision is what hand tool to use: Should it be a hand saw or a chain saw? In the case of water management, the decision is what computer tool or model to use. Jackson (1982) suggests that to select the best model, one should follow the procedure illustrated by Figure B-1. In the case of flood damage reduction planning, the information identified in step 1 of this procedure typically includes:

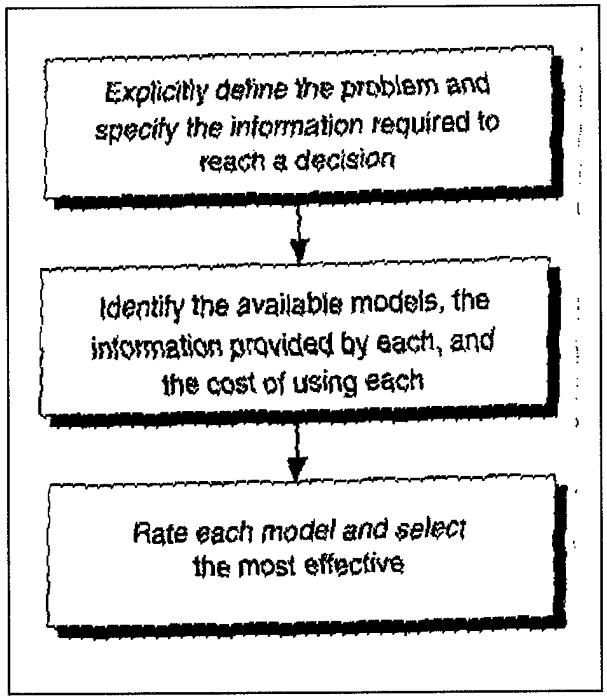

Figure B-1. Steps in selecting the appropriate model

- Stream-discharge time series or peaks.
- Volume time series or totals.
- River or reservoir water depth time series or maximums.
- Probabilities (frequencies) of extreme discharge, volume, or depth magnitudes.
- Inundated-area geometry.
- Landform changes due to erosion or deposition; or
- Economic, social, or environmental costs and benefits associated with any of these items.

The remainder of this appendix is devoted to step 2: identifying available models that can provide this information.

c. Classification of the computer models. The information provided by a computer model is correlated directly with the processes modeled. For flood damage reduction planning, the critical processes include those

shown in Table B-1. Some computer models focus not on the processes but on system accomplishments, so accomplishment models are included in this appendix as an additional classification. Accomplishment models may simulate critical processes as a secondary function, but their primary function is to use information from such a simulation to evaluate economic, social, or environmental benefits and costs.

d. A warning.

(1) Scott McNeally, chairman of a Sun Microsystems, suggested that "... the shelf life of biscuits and technology is about the same (NY Times, 27 March 1993)." Accordingly, the hydrologic engineer is cautioned that the state-of-practice in computer modeling changes rapidly. He or she should consult HQUSACE, WES, and HEC staff for information on computer model updates or new computer models before selecting for application one of the models described in this appendix.

(2) In unusual circumstances, the computer models described herein will not provide the information required. In those cases, the hydrologic engineer may refer to theses and dissertations, project reports, and technical journals (including AGU's Water Resources Research, ASCE's Journal of Hydraulic Engineering, ASCE's Journal of Water Resources Planning and Management, and AWRA's Water Resources Bulletin) to identify an appropriate tool. DeVries and Hromadka (1993), Renard, Rawls, and Fogel (1982), Larson et al. (1982), and WMO (1975) have published reviews that may be helpful.

B-2. Runoff-Process Models

a. HEC-1. HEC-1 is a single-event model that estimates runoff from precipitation with a spatially and temporally lumped description of a catchment (USACE 1990b). HEC-1 incorporates a variety of conceptual or quasi-conceptual mathematical models; the user specifies through input which of these are used. Parameters for the various mathematical models also are specified by user input. HEC-1 includes a parameter estimation routine that will estimate most runoff model parameters if proper hydrometeorological data are available. HEC-1 provides stream-discharge time series and peaks, and volume totals for decision making.

Table B-1
Critical Processes to Model for Flood Damage Reduction Planning

Process	Description
Catchment-runoff	These are the processes that govern how precipitation that falls on a catchment runs off that catchment. Runoff processes include evaporation, transpiration, infiltration, percolation, interflow, overland flow, and baseflow. Modeling these processes provides information on stream-discharge time series or peaks, and volume time series or totals.
Fluvial	These are the processes that govern fluid flow in an open channel when that fluid is subjected to external forces. Modeling these processes provides information on river or reservoir depth time series or maximums, and inundated-area geometry.
Alluvial	These are the processes that govern the erosion and deposition of sediment due to flow in an open channel. Modeling these processes provides information on landform changes due to erosion or deposition, river or reservoir water depth time series or maximums, and inundated-area geometry.
Pressure-flow	These are the processes that govern how water flows under pressure in closed conduits. For water excess management in urban settings, these processes are often planned to function as pressure conduits for the design flow or greater events (ASCE/WEF 1992).
Statistical	Physical, chemical, or biological processes exhibit randomness and variability that cannot be accounted for with models of the behavior of a system. Models of statistical processes recognize this and seek to describe the randomness and variability by establishing an empirical relationship between probability and magnitude. A statistical-process model yields information on probabilities associated with extreme discharge, volume, or depth magnitudes.

(1) Mathematical models included in the computer model. The runoff process, as represented in HEC-1, is illustrated by Figure B-2. The mathematical models incorporated in this representation include those shown in Table B-2. In addition to runoff process models, HEC-1 includes the following fluvial process models for routing hydrographs: Muskingum, kinematic wave, modified Puls (level pool), and Muskingum-Cunge. The user may select any one appropriate for a given stream reach. As with other mathematical models included in HEC-1, any combination of these may be used. Parameters are defined with user input.

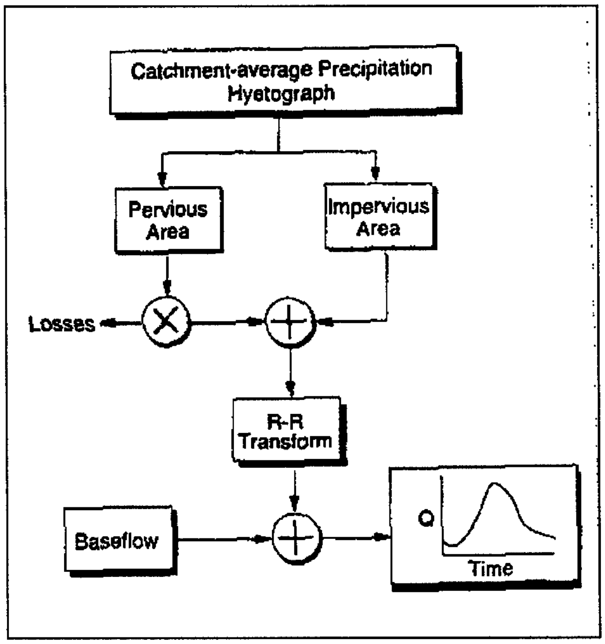

Figure B-2. HEC-1 representation of runoff process

(2) Complex catchment representation. With the runoff and fluvial process models used in combination, large catchments in which parameters or precipitation vary spatially can be analyzed. To do so, the catchment is subdivided, the runoff-process models are used to compute runoff at various locations, and the routing models are used to account for flow in stream channels to common points. Figure B-3 illustrates this approach. First runoff is computed for subcatchment 1 with the runoff process models. The resulting hydrograph represents the flow at control point A. This hydrograph is routed from A to B with a fluvial process model. The hydrograph of runoff from subcatchment 2 is computed and added to the routed hydrograph. This yields an estimate of total runoff, accounting for spatial variation in rainfall and catchment characteristics.

(3) Input and output. To estimate catchment runoff with HEC-1, the user must provide the input shown in Table B-3. Output from HEC-1 includes the following: A summary report of the user's input; for each

Table B-2
Mathematical Models Included in HEC-1

Model Type	Description
Loss	To account for infiltration, depression storage, and other reductions in volume of precipitation on pervious areas in a catchment, HEC-1 offers the following alternatives: initial loss plus uniform rate; SCS curve number; 4-parameter exponential; Holtan's; and Green and Ampt. The user may select any one of these for a catchment. For complex catchments that are subdivided for analysis, the user can select combinations of the loss models.
Snowfall and snowmelt	These models simulate snowfall formation and accumulation and estimate runoff volumes due to snowmelt. The snowfall model permits division of a catchment into elevation zones. The user specifies a time series of temperatures for the lowest, and the model estimates temperatures for all others with a lapse rate. Precipitation is assumed to fall as snow if the zone temperature is less than a user-defined freezing threshold. Melt occurs when the temperature exceeds a user-defined melting threshold. Snowfall is added to and snowmelt is subtracted from the snowpack in each zone. Snowmelt may be computed with either a degree-day model or an energy-budget model.
Runoff transform	Runoff volumes may be transformed to runoff hydrographs in program HEC-1 with either a unit hydrograph model or via solution of the kinematic-wave simplification of the St. Venant equations.
Baseflow	HEC-1 incorporates a single model of baseflow, which is based on the assumption that drainage of water added to storage in a catchment can be modeled well as exponential decay.

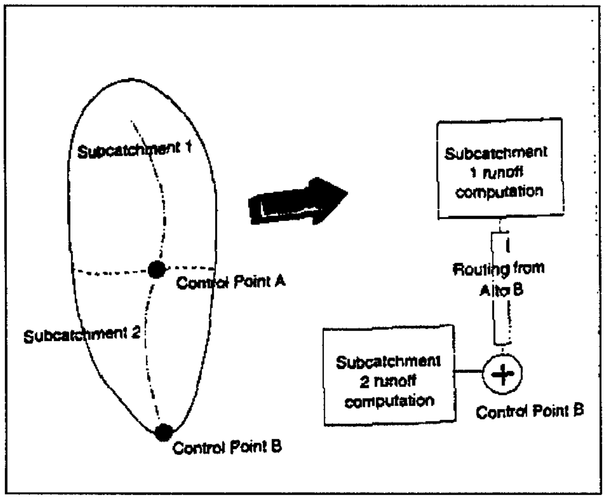

Figure B-3. Illustration of complex catchment modeling by subdivision

subcatchment, a report of the average-precipitation depth, the loss, and the excess for each simulation step, plus a report showing the computed runoff hydrograph ordinates; for each stream reach modeled, a report of the outflow (downstream) hydrograph ordinates; and various summary output tables that show the discharge peaks and times of peak at system control points.

(4) Utility programs. HEC has developed utility programs that simplify use of HEC-1; two are summarized in Table B-4.

B-3. Fluvial-Process Models

a. HEC-2. HEC-2 solves the equations of one-dimensional, steady, gradually varied flow to predict water-surface elevation along a natural or constructed open channel (USACE 1982a). Water-surface profiles in either subcritical or supercritical regime can be computed. HEC-2 also incorporates conceptual and empirical models that allow analysis necessary for common designing, planning, and regulating problems. These special capabilities are summarized in Table B-5.

(1) Mathematical models included.

(a) Given a complete description of the geometric boundaries which contain the flow in an open channel, HEC-2 estimates the average flow depth and velocity in the prescribed cross sections by solving the one-dimensional energy equation. This formulation assumes that flow is steady and gradually varied, with localized rapidly varied flow, such as at weirs or culvert inlets; flow is turbulent, and fully rough, with viscous forces playing a minor role; flow is homogeneous, with constant fluid density throughout the flow field; flow can be adequately characterized by movement in a single direction; and pressure distribution at a cross section is hydrostatic. Violation of one or more of these assumptions does not necessarily mean that results of analysis with HEC-2 are wrong. Instead, the relative effect of these assumptions upon the results of a particular application must be evaluated.

Table B-3
HEC-1 Input

Input Item	Description
Precipitation	The precipitation may be provided as catchment average depth or as depths observed at gages. The user must provide a temporal distribution of precipitation: this may be the historical observation at a gage, or it may be a design-storm distribution.
Catchment and channel physical characteristics, including characteristics of water-control facilities	The user must delineate catchment boundaries and define, via input, the catchment area. If the catchment is subdivided for analysis, the user must define, through the sequence of input, how the system is schematized for modeling. If the stream system includes water-control facilities, such as detention ponds, the characteristics of these must be specified also.
Model parameters	User must specify all appropriate loss-model, runoff transform model, baseflow model, and routing model parameters.
Simulation specification	User must specify the time step and duration of the simulation, subject to constraints imposed by the available computer memory.

Table B-4
Utility Programs for and Specialized Versions of HEC-1

Program	Description
HEC-DSS (USACE 1990a, 1991)	This is a time-series database management system (DBMS). It creates specially formatted random-access files, with a hierarchical system of record names to expedite storage and retrieval of data in the files. Data in the DBMS may be accessed through a set of front-end utility programs that permit data entry, reporting, charting, and database housekeeping. Further, the data can be accessed via a FORTRAN library of routines that read, write, and otherwise interact with database files. It is through this library that HEC-1 (and many other models from HEC) retrieves data from and files data in the database.
HMR-52 (USACE 1984)	This program computes catchment-average precipitation for probable maximum design storms (PMS), using criteria established by the National Weather Service (NWS) for catchments east of the 103rd meridian in the United States. The storm may be used, in turn, as input to HEC-1 to estimate the probable maximum flood (PMF) runoff. This extreme discharge is the basis for dam-safety analysis.

Table B-5
Special Capabilities of HEC-2

Capability	Description
Treatment of effective flow areas	Several options are available to restrict flow to certain portions of a given cross section. This is often required because of sediment deposits, floodplain encroachments, oxbow lakes, etc.
Analysis of bridge and culvert losses	The energy loss due to bridge piers and culverts can be estimated.
Analysis of channel	Six methods of specifying floodplain encroachments are available. The equal conveyance reduction method is used to determine the floodway boundaries for a flood insurance study.
Evaluation of channel improvement	Natural river cross-section data may be modified simply with the channel improvement option. This allows simulation of the effects of excavating a compound trapezoidal channel section into the natural section.
Calibration of high water marks	When high water marks are known for a specified discharge, HEC-2 can estimate the effective Manning's *n* value necessary to reproduce this observed elevation.
Development of storage-outflow function	HEC-2 includes the capability to develop a storage volume versus relationship for a river reach. This can, in turn, be used for streamflow routing with the modified Puls and other simple fluvial process models.
Analysis of split flow	For flow splits (such as at diversion structures, levee overtoppings, etc.) HEC-2 balances the energy grade line elevations at the split and downstream confluence. Weir flow, normal depth, or a diversion rating curve may describe the hydraulics of the split.
Simulation of flow in ice-covered streams	Water-surface profiles with a stationary, floating ice cover can be estimated. The user must provide the thickness and effective n value of the ice cover.

(b) HEC-2 estimates the total energy loss between two adjacent sections as the sum of frictional energy loss due to channel roughness; form-energy loss due to expansion and contraction; and energy loss due to flow through structures, such as a bridges, culverts, or weirs. The frictional energy loss is the product of the average energy grade line slope and the distance between cross sections. This energy grade line slope at a section is computed with Manning's equation. Several schemes are available in HEC-2 for determining the average energy grade line slope between two cross sections: arithmetic, geometric, or harmonic mean energy slope at adjacent cross sections, or the average conveyance at adjacent cross sections. HEC-2 includes a contraction/expansion energy loss

model that estimates that loss as a function of the difference in velocity head between two cross sections.

(c) By computing the energy loss between a river cross section with a known water-surface elevation and an adjacent cross section, the water-surface elevation at the adjacent section can be determined. For subcritical flow, the computations start with a known relationship between discharge and water-surface elevation at the downstream boundary of the fluvial system and proceed in an upstream direction until the water-surface elevation is computed at each cross section. For supercritical flow, the computations start with a known water-surface elevation at the upstream boundary and proceed in a downstream direction.

(2) Input and output. HEC-2 is a generalized computer program. The user must therefore provide all stream characteristics and boundary conditions via input. For a simple application, the input requirements are as shown in Table B-6. A variety of output data may be selected by the user, including a report of computed water-surface elevation, velocity, and other pertinent characteristics of flow at each channel cross section. HEC-2 will prepare an electronic file with the computed results for subsequent access by graphing and reporting utilities.

b. UNET. Program UNET simulates one-dimensional, unsteady flow through either a simple open channel, a dendritic system of open channels, or a network of open channels (Barkau 1985, USACE 1993b). This permits analysis of diversions and confluences in a looped system, including systems in which the direction of flow may reverse. UNET has the capability to model also flow in lakes, bridges, culverts, weirs, and gated spillways, using mathematical models that are essentially the same as those included in HEC-2.

(1) Mathematical models included. UNET solves a linearized finite-difference approximation of the full one-dimensional, unsteady flow equations (Barkau 1985). The solution algorithm uses sparse matrix techniques with Gaussian reduction.

(2) Input requirements and output. The input required for UNET is similar to that required for HEC-2. Additional input is required to describe the interconnection of stream segments, and location of lakes and storage elements. UNET uses the HEC-DSS described in Table B-4 to store boundary conditions, such as rating curves and hydrographs. Table B-7 defines UNET input requirements. Unsteady flow models typically produce large reports of computational results, and UNET is not

Table B-6
Input Required for HEC-2

Input Item	Description
Flow regime	The user must assess the location of normal depth relative to critical depth for each application. For a subcritical flow regime, cross-section data are specified progressing upstream. For supercritical flow regime, data are specified progressing downstream. For unknown or mixed regimes, multiple input data sets are prepared and results combined, as discussed in the HEC-2 user's manual.
Starting boundary condition	HEC-2 solves the one-dimensional energy equation for a given stream state, so the starting water-surface elevation must be specified. This can be input directly or estimated by the program.
Discharge	The steady flow discharge must be specified for each stream segment. This may change along the profile in order to include effects of tributaries, diversions, etc.
Energy loss coefficients	For a basic application of HEC-2, user must specify Manning's *n* for the main channel, left and right overbanks. User may specify contraction and expansion loss coefficients.
Cross-section geometry	Boundary geometry for the analysis is provided by a series of elevation versus station coordinate points at each cross section. Cross sections are required at representative locations throughout the reach, but especially where slope, conveyance, or roughness change significantly.
Reach length	The distance between cross sections must be specified to permit computation of the turbulent energy loss due to boundary roughness. HEC-2 allows input of separate reach lengths for the main channel, left and right overbanks to describe curved channels, river meanders, etc.

an exception. The model computes and reports depths, velocities, and other pertinent flow characteristics at each cross section for each time step of the finite-difference solution of the flow equations. These results may be filed with the HEC-DSS and subsequently plotted with DSPLAY, the graphing program of the database management system.

c. HIVEL2D Program.

(1) HIVEL2D solves the two-dimensional, depth-averaged, unsteady flow equations for high velocity flow in a channel. This computer program is specifically designed to evaluate flow behavior at bridge piers, transitions, confluences, curves, etc. in lined flood control channels where the dominant flow regime is supercritical. The program can also be used for subcritical flow situations that may transition into or out of supercritical flow. Due to the way the differential equations of flow are formulated and solved, HIVEL2D can accurately capture the effects of shocks. Assumptions in the mathematical model include the following: The pressure distribution is hydrostatic; the coriolis, buoyancy, and wind resistance effects are insignificant; and vertical accelerations are unimportant. These assumptions are typically valid for most channels with slopes flatter than 0.05. At present the mathematical model does include third order Boussinesque terms which describe shorter waves such as those caused by reflection off of a channel wall. This means that guidance in EM 1110-2-1601 and possibly physical modeling efforts should accompany an application of HIVEL2D.

(2) For the Los Angeles River, HIVEL2D was successfully applied in conjunction with physical modeling efforts in order to evaluate the ability of existing bridges to pass the design flow and to determine the effects of proposed bridge modifications. Table B-8 describes the general capabilities of the model, and Table B-9 describes the input requirements.

B-4. Alluvial-Process Models

a. HEC-6. HEC-6 models the effects of river sediment transport and resulting changes in the flow boundaries with a one-dimensional representation of the open-channel flow (USACE 1993b). The program computes changes in riverbed profiles for a single flood event or for a long-term sequence of flows. HEC-6 provides information on depths and landform changes due to erosion or deposition. Thus it can be used to evaluate the movement of a stream.

(1) Mathematical models included.

(a) HEC-6 solves the one-dimensional energy equation using a computation technique similar to that included in computer model HEC-2. HEC-6 does not include the empirical models for bridge and culvert energy losses, but it does allow for the specification of an internal elevation-discharge boundary condition, the development of which can be accomplished using HEC-2. Transport calculations are made for a control volume defined using the cross-section locations and an assumed

Table B-7
Input Requirements for UNET

Input Item	Description
Channel geometry	Each cross section is input in HEC-2 format. The cross-section file is arranged in a reach-by-reach order with the upstream and downstream connectivity specified. This allows changes to be made without reordering the entire data file.
Boundary conditions	Discharge hydrographs or water-surface elevation rating curves must be specified for each terminal reach boundary.
Initial conditions	The initial depth and velocity must be specified for each cross section. The model has the ability to save the final results of one application to be used as the initial conditions file for another application.
Channel roughness	A value of Manning's *n* is required for each cross section. Contraction and expansion coefficients and weir coefficient may also be specified.

Table B-8
Special Capabilities of HIVEL2D

Input Item	Description
Flow regime	Both supercritical and subcritical flow as well as the associated horizontal accelerations or shocks can be simulated.
Channel geometry	The solution uses both triangular and quadrilateral finite elements, thus allowing complex geometries to be simulated. A special formulation of the solution technique allows the simulation of sloped channel sidewalls.
Energy losses	A value of Manning's *n* can be specified for each element in the computational grid. The model has the ability to compute the turbulent eddy coefficients based on local hydraulic properties and bed roughness.
Output format	The program can be used with standard graphical interfaces such as TABS-II in order to view plots of computed depth and velocity.

Table B-9
Input Requirements for HIVEL2D

Input Item	Description
Channel geometry	Each node of the finite element grid requires the specification of both x and y horizontal coordinates, and the elevation of the bed of the channel. The node connectivity list for each element is also required. The model has the ability to create the finite element grid by the specification of centerline bearings, wall offsets, curvature radii, etc.
Boundary conditions	Depth and/or discharge boundary conditions must be specified. For unsteady flow applications, a hydrograph and/or rating curve is used.
Initial conditions	The initial depth and velocity must be specified at each computational node in the solution network. The model has the ability to save the final results of one application to be used as the initial conditions file for another application.
Channel roughness	A value of Manning's *n* is required for each element of the computational grid.

depth of alluvial deposits. The computed energy slope, depth, velocity, and shear stress at each cross section are used to compute the sediment transport capacity at each cross section. These rates, along with sediment supply rate and armoring potential, are used for volumetric accounting of sediment movement through the system. The amount of scour or deposition is computed by dividing the surface area of the mobile boundary into the change in sediment volume. A new water-surface profile is then computed for the updated channel geometry.

(b) Sediment transport rates in HEC-6 are computed for 20 different grain size categories ranging from clay (less than 0.004 mm) through silt (less than 0.063 mm) up to large boulders (2,048 mm). A variety of sediment transport equations, based on either cohesive or noncohesive theory, can be selected for the transport capacity calculations. Mathematical models of incipient motion, channel bed armoring, grain size sorting, and particle entrainment are also included in HEC-6.

(c) To account for unsteady flow with HEC-6, a hydrograph is discretized into a series of steady flows, and a water-surface profile is computed using a standard step backwater approach. This procedure is repeated until the entire event has been simulated.

(d) Due to the one-dimensional formulation, HEC-6 does not represent the multi-dimensional nature of sandbar formation, secondary flow currents, and streambank failure.

(2) Input and output. HEC-6 requires all of the information necessary for a one-dimensional fluvial

model, including a complete description of the geometric boundaries of the channel that contains the flow, definition of the flow regime, and specification of energy loss coefficients. In addition, the user must develop and provide information on sediment grain-size distribution; sediment specific gravity, shape factor, unit weight, and fall velocity; and boundary conditions. HEC-6 output includes reports of both hydraulic and sediment-transport calculations. The basic level of output data includes a report of initial conditions, hydraulic calculations, sediment transport calculations, accumulated sediment volumes, and overall bed elevation changes.

b. TABS-2. TABS-2 is a collection of generalized computer programs and utility codes integrated into a numerical modeling system for studying two-dimensional hydraulics, transport, and sedimentation processes in rivers, reservoirs, bays, and estuaries (EM 1110-2-1416, Thomas and McAnally 1985). Figure B-4 illustrates the interaction of the components of TABS-2.

(1) Mathematical models included. TABS-2 solves the two-dimensional, depth-averaged momentum and continuity equations, for either steady or unsteady flow. TABS-2 uses a finite element technique and computes, for each node of the finite-element representation, flow depth and longitudinal and lateral velocities. The sedimentation component of the model then computes the transport capacity using the two-dimensional convection-diffusion equation with bed source terms. The actual transport is based on sediment availability. TABS-2 can handle both cohesive and noncohesive sediment transport.

(2) Input and output. The user must define the finite-element grid. In addition to the grid network data, the user must provide information on initial bed material sizes for each element. As with the other alluvial process models, the inflowing sediment load and hydrograph must be specified by the user. TABS-2 will provide detailed reports of all computations. To aid the user in digesting this mass of output, TABS-2 includes also a postprocessor that displays the results of computations graphically. This graphical output includes velocity vector plots, contour plots of scour/deposit depths, and shear stress variations.

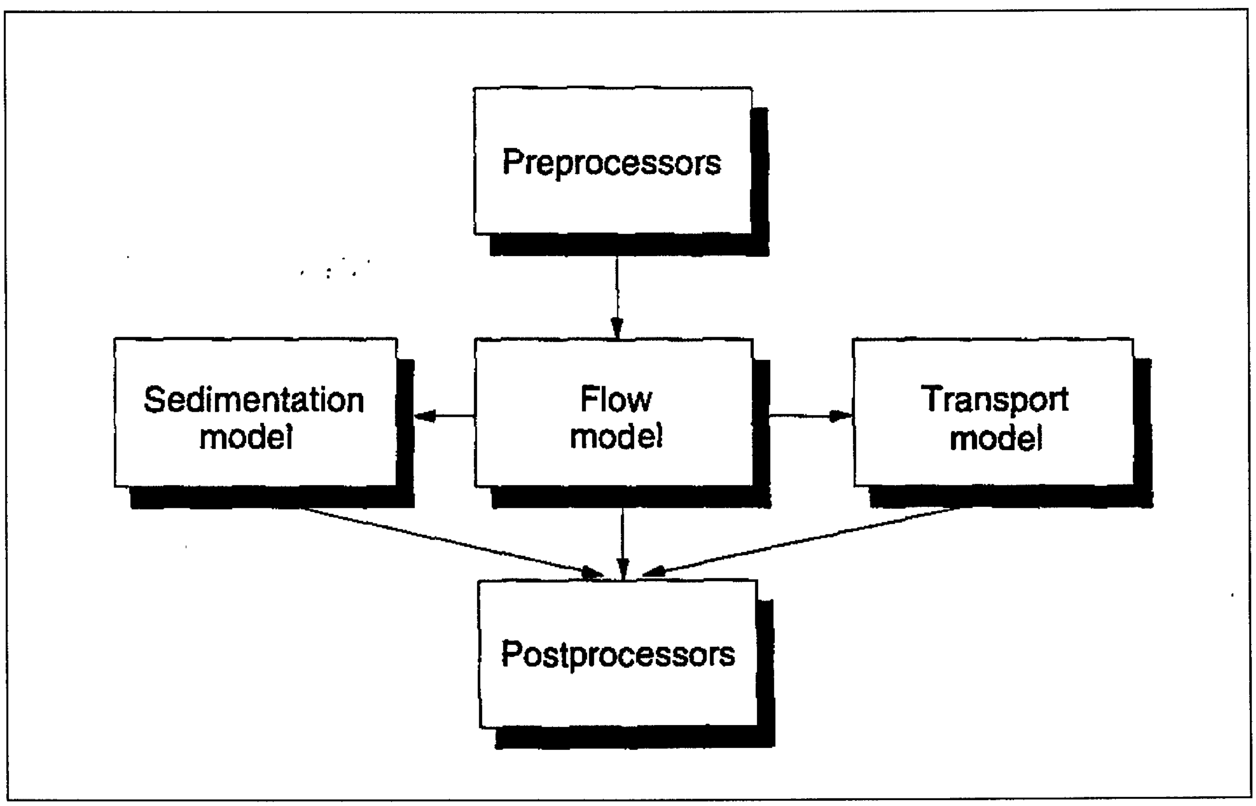

Figure B-4. Components of TABS-2

c. SAM. The SAM program, entitled Hydraulic Design Package for Flood Control Channels, was developed to provide guidance on the width, depth, and slope of stable channels in alluvial materials. The mathematical model includes one-dimensional, steady flow hydraulic calculations, sediment transport capacity calculations, and sediment yield calculations based on flow duration. SAM is, in a sense, a scaled back version of HEC-6. It does have additional capabilities, however, and these are listed in Table B-10. The input is largely interactive. SAM also has the ability to read TAPE95 output files from HEC-2 in order to retrieve hydraulic properties.

B-5. Statistical-Process Computer Models

HEC-FA. In the United States, a number of Federal agencies conduct annual maximum discharge frequency analysis for decision making. Until 1967, each agency established its own methods and procedures for the analysis, leading to occasional differences in estimates of quantiles or probabilities. To promote a consistent approach, a multi-agency committee of the USWRC studied alternatives and recommended the log-Pearson type III distribution for use by U.S. Federal agencies (Interagency Advisory Committee 1982). The committee recommended also procedures for treating small samples, outliers, zero flows, broken and incomplete records, and historical flood information. Program HEC-FA (USACE 1992a) implements these guidelines.

a. Mathematical models included. HEC-FA fits a Pearson type III statistical model (distribution) to logarithms of an observed flood series, using modified method-of-moments parameter estimators. In simple terms, this statistical model estimates the discharge that is exceeded with specified probability. Table B-11 shows the analysis procedures used by the model in fitting the distribution. The Interagency Advisory Committee guidelines (also known as Bulletin 17B) and EM 1110-2-1415 describe the procedures in more detail.

(2) Input requirements and output. HEC-FA provides information on probabilities (frequencies) of extreme discharge magnitudes. To do so, it requires the input shown in Table B-12. Output from HEC-FA includes a summary report of the user's input; computed sample statistics and estimated model parameters; a report of the computed frequency function, showing selected quantiles; and plots of the frequency function.

B-6. Accomplishment Models

The computer models described earlier provide information on system behavior; they simulate processes by which a system input is transformed to a system output. But for informed damage-reduction planning, the hydrologic engineer must provide information on system accomplishment: the consequence of a particular system output or a particular state of the system. Several of the models described include the capability to assess accomplishment. For example, HEC-1 includes routines to model detention-structure accomplishment, given hydrographs computed with the runoff process models it includes. But for more detailed analysis, computer models designed especially for evaluation are available. Three are described here: EAD, a flood-damage evaluation model; HEC-5, a reservoir-system evaluation model; and HEC-IFH, an interior-area-protection evaluation model.

Table B-10
Special Capabilities of SAM

Input Item	Description
Stable channel design	SAM has the ability to predict stable channel dimensions including width, depth, and slope, for a given discharge.
Sediment transport	A wide range of sediment transport equations can be selected. SAM has the ability to produce sediment transport versus discharge curves for a number of different transport functions in a single execution.
Sediment yield	SAM can compute average annual sediment yield for a stream based on the computed transport capacity and a specified flow duration curve. Most of the output can be displayed graphically and in printed numeric format.
Output format	The program creates a DSS file containing time series data, rating curves, and maximum water-surface elevation profiles.

Table B-11
HEC-FFA Features

Features	Analysis Procedure
Parameter estimation	Estimate parameters with method of moments; this assumes sample mean, standard deviation, skew coefficient = parent population mean, standard deviation, and skew coefficient. To account for variability in skew computed from small samples, use weighted sum of station skew and regional skew.
Outlier	These are observations that "... depart significantly from the trend of the remaining data." Model identifies high and low outliers. If information available indicates that high outlier is maximum in extended time period, it is treated as historical flow. Otherwise, outlier is treated as part of systematic sample. Low outliers are deleted from sample, and conditional probability adjustment is applied.
Zero flows	If the annual maximum flow is zero (or below a specified threshold), the observation is deleted from the sample. The model parameters are estimated with the remainder of the sample. The resulting probability estimates are adjusted to account for the conditional probability of exceeding a specified discharge, given that a nonzero flow occurs.
Historical flood information	If information is available indicating that an observation represents the greatest flow in a period longer than that represented by the sample, model parameters are computed with historically weighted moments.
Broken record	If observations are missing due to "... conditions not related to flood magnitude," different sample segments are analyzed as a single sample with size equal to the sum of the sample sizes.
Expected probability adjustment	The basic procedure prescribed in Bulletin 17B yields a median discharge frequency function. This adjustment is made to the model results "... to incorporate the effects of uncertainty in application of the [frequency] curve." The resulting mean or expected frequency function is appropriate for economic analysis.

Table B-12
Input Required for HEC-FA Program

Input Item	Description
Time series	Sample series of unregulated, annual-maximum flows that are free of climatic trends, representative of constant watershed conditions, and from a common parent population.
Historical data	If historical flow data outside the continuous time series are available, the user must identify these.
Executive specifications	The user may select from among various plotting positions for visually inspecting the goodness-of-fit, and from among various reports and plots of results.
Parameters	HEC-FA estimates the log Pearson type III parameters from sample statistics. The sample statistics are computed from the input series. However, if desired, the user may specify the sample statistics, thus overriding the computation. Further, the user must specify the regional skew coefficient if the weighting scheme of Bulletin 17B is to be used.

a. EAD. The objective of the HEC-EAD (Expected Annual Flood Damage) program (USACE 1989a) is to compute inundation damage and inundation-reduction benefit as described in Chapters 1 and 2 of this manual, thus permitting evaluation of existing flood hazard and of the anticipated accomplishment of proposed damage-reduction measures.

(1) Mathematical models included in the computer model. Average annual damage, also properly called the

expected annual damage, is computed by integrating the cumulative distribution function (cdf) of annual damage. In the simplest application, EAD uses a numerical integration scheme to integrate a user-provided damage-frequency function and reports the results. These computations can be performed for various damage categories for any number of reaches (subdivisions of the floodplain). Damage-frequency functions are not commonly available, but are derived from statistical, fluvial, and economic data or models, as illustrated in Figure 2-1. The functions may represent the existing without-project, existing with-project, future without-project, and/or future with-project state of the floodplain. EAD will perform this manipulation for any alternative conditions defined by the user. The functions shown in Figure 2-1 may change with time. EAD includes the appropriate discounting formulas as required by the Principles and Guidelines to "... convert future monetary values to present values."

(2) Input and output. Table B-13 shows the input required for program EAD. EAD output includes the following: a summary report of the user's input; the derived damage-frequency functions, sorted by reach, for each damage category, plus the aggregate function, for the existing, without-project condition, and for each alternative condition defined by the user; a report of the computed average annual damage, sorted by reach, for each damage category and the aggregate, for the existing, without-project condition and for each alternative condition defined by the user. The inundation-reduction benefit of each with-project condition is displayed also.

(3) Utility programs. The HEC has developed utility programs that simplify use of EAD or provide additional capabilities. The SID program provides data management capabilities for the numerous stage-damage functions typical of a major flood-control study (USACE 1989b). It yields input in the format required for EAD. The FDA package is a complete ensemble of flood-damage analysis models (USACE 1988a). It includes EAD, SID, and utility programs that permit linkage with statistical and fluvial process models through the HEC-DSS.

b. HEC-5. Program HEC-5 models a reservoir or system of reservoirs that are operated to manage excess water (USACE 1982b). Other computer models, including HEC-1, can simulate the operation of a detention structure in which that operation is a function of the properties of the outlet works. HEC-5, however, simulates operation that is a function of both the properties of the outlet works and an operator's specification of the manner in which the reservoirs should function. With HEC-5, storage in each reservoir in a system is divided into zones. Within each zone, the user defines indexed storage levels. The model will simulate operation to meet specified system constraints and to keep system reservoirs in balance, with each at the same index level. System constraints that may be modeled are summarized in Table B-14. In addition to modeling reservoir flood-control operation, HEC-5 includes algorithms for modeling reservoir system operation for conservation purposes.

(1) Mathematical models included in the computer model. HEC-5 includes various models for streamflow routing, including the Muskingum and storage models. It includes also a reservoir storage routing model. For reservoirs with hydroelectric power generation facilities, an energy production model is included.

(2) Input and output. Input required includes the following: reservoir inflows and intermediate-area runoff, reservoir evaporation rates, routing-model parameters, description of the reservoirs and the physical relationships of reservoirs, channel, etc., and a definition of the operating policy. HEC-5 output includes the following: a summary of the user's input; for each reservoir, a summary

Table B-13
Input Required for EAD Program

Input Item	Description
Job specification	User must define discount rate, period of analysis.
Statistical function	User must provide either discharge versus probability, stage versus probability, or damage versus probability function.
Other functions	Depending on the form of the statistical function provided, user must provide other functions necessary to derive a damage versus probability function. These may include stage-damage and/or stage-discharge functions.

Table B-14
HEC-5 Flood-Control Operation Rules

Constraint on Release Made	Condition
Release to draw storage to top of conservation pool without exceeding channel capacity at reservoir or downstream points for which reservoir is operated	Storage is between top of conservation pool and top of flood-control pool
Release equal to or greater than minimum desired flow	Storage greater than top buffer storage
Release equal to minimum required flow	Storage between top inactive and top of buffer pool
No release	Storage below top of inactive pool
Release required to satisfy hydropower requirement	If that release is greater than controlling desired or required flows for above conditions
Release limited to user-specified rate of change	Unless reservoir is in surcharge operation
No release that will contribute to flooding downstream	If flood storage is available
Release to maintain downstream flow at channel capacity	If operating for flood control
Release from reservoir at greatest level	If two or more reservoirs on parallel streams operate for common downstream point
Release to bring upper reservoir to same index level as downstream reservoir	If two reservoirs are in tandem

of inflows, releases, and storage for the period of analysis; for each system control point, a summary of flows for the period of analysis; and if flood-damage relationships are provided, a summary of damage at each location. HEC-5 also includes links to HEC-DSS. Thus flood hydrographs can be computed and filed in the database by a catchment-process model, then retrieved for reservoir-accomplishment analysis with HEC-5.

c. HEC-IFH. HEC's Interior Flood Hydrology program, HEC-IFH, was developed specifically for hydrologic analysis of interior areas—areas protected from direct riverine, lake, or tidal flooding by levees, floodwalls, or seawalls (USACE 1992b). Using either a continuous or event simulation, it will determine stage-frequency and flooding duration within the interior area. The program is described in detail in a user's manual (USACE 1992b).

(1) Mathematical models included. HEC-IFH includes runoff-process, fluvial-process, pressure-flow process, and statistical-process models. The runoff-process and fluvial-process (routing) models are essentially the same as those included in program HEC-1. These are described in paragraph B-2. HEC-IFH includes also a pond-operation model that accounts for discharge by gravity-outlet flow and pumping and a culvert hydraulics model to simulate the outlet behavior.

(2) Input and output.

(a) HEC-IFH is an interactive program: Program functions are user controlled through a set of menus, and user input is provided on data-entry screens. In addition to the input required for runoff and routing computations with program HEC-1, HEC-IFH requires the input shown in Table B-15.

(b) HEC-IFH output includes input summaries; results of simulation, either for the continuous period or for individual events; aggregate time-period performance summaries for continuous simulation; and stage-frequency functions. Most of these results can be presented in tabular or graphical format.

Table B-15
HEC-IFH Input

Input Item	Description
Pond characteristics	Interior-area pond elevation versus area versus volume relationship
Gravity outlet characteristics	Description of maximum 25 outlets, to include type, length, elevations, and gate descriptions
Pump characteristics	Description of maximum 10 pumps, to include total head versus discharge capacity versus efficiency, pump-on and pump-off elevations
Additional hydrologic data	Stage hydrograph for exterior channel, either continuous or for single event. External flow into system, overflow, diversion, seepage